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AIRCRAFT FUEL TANK INERTING BY MEANS OF FUEL CELL FUEL FOGGING

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MCDONNELL AIRCRAFT COMPANY

TECHNICAL REPORT AFAPL-TR-69-46

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Air Force Aero Propulsion Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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AIRCRAFT FUEL TANK INERTING BY MEANS OF FUEL CELL FUEL FOGGING

E. W. Wiggins
Q. C. Malmberg

FOREWORD

This report was prepared by the Power and Fluid Systems Department of McDonnell Aircraft Company, McDonnell Douglas Corporation. The work reported herein was carried out under Contract No. F33615-68-C-1660, Project No. 3048, "Fuel Fog Fuel Cell Inerting System", and was administered by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The period covered by this report is July 1, 1968 to January, 1969.

This technical report has been reviewed and is approved.

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ABSTRACT

Inerting of aircraft fuel tanks to eliminate fires and explosions can be accomplished by a number of methods. Oxygen dilution with inert gases, flame arresting with open cell foam and chemical quenching using halogenated hydrocarbons are some of the more successful methods. Another approach, the subject of this report, is to maintain the ullage fuel rich by employing some of the liquid fuel itself in the form of a fog. The fuel fog system works on the principle that finely divided liquid fuel (fog) acts as if it were in the vapor state, adding to the natural fuel vapor concentration, thereby driving the tank ullage space over-rich. The system consists of a distribution manifold with fog nozzles located to produce a uniform fog distribution throughout the fuel cells under all degrees of ullage and dynamic flight conditions. Since the fuel itself is the inerting material; weight, volume and logistic penalties are low. The first phase of the program was to define the fuel fog concentration and distribution with respect to various nozzle configurations, grouping, and flow rates under typical aircraft operating parameters. Qualitatively, it was concluded that a uniform fog distribution is no problem due to the high turbulence observed in the visualization chamber. Quantitative concentration data were inconclusive due to sampling difficulties which lead to data scatter. The Phase II ignition studies have defined the dynamic flammability zones for JP-4 using the most effective fog inerting nozzle with three ignition sources; 14 joule capacitance spark, 23 joule induction spark, and incendiary, equivalent in weight and energy to a .50 caliber A.P.I. In the parallel ignition study program it was determined that the most effective inerting off-the-shelf nozzle is a hydraulic impingement type manufactured by Bete Fog Nozzle Company. This conclusion was brought about by the direct comparison of inerting characteristics of many different nozzles of the hydraulic and pneumatic type. Pre-termination of Phases III and IV, the gunfire tests and the comparison of the subject system with other candidate systems was mutually agreed upon due to limited inerting capabilities shown by the fuel fog system.

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SECTION I

INTRODUCTION

Operational experience has shown that fuel fires and explosions, direct or indirect, are responsible for a major portion of aircraft combat losses. The type of fuel is immaterial in that incendiary projectiles and high velocity fragments do not recognize lean limits, and rich mixtures are negated during altitude change recompression. Thus, an artificially inerted tank is the only safe tank.

Inerting of aircraft fuel tanks to eliminate fires and explosions can be accomplished by a number of methods. Oxygen dilution with inert gases, flame arresting with open cell polyurethane foam and chemical quenching using halogenated hydrocarbons are some of the more successful methods. Artificially produced and maintained fuel rich ullage by means of liquid fuel fogging is another approach and is the subject of this evaluation and demonstration program.

The fuel fog inerting system is based on two principles, first that all fuels have a lean and rich concentration limit of flammability, and secondly, that finely divided suspended liquid fuel (fog) acts with respect to ignition and flame propagation as if it were in the vapor state. Since the rich limit is defined as the concentration of fuel vapor to air above which flame propagation cannot occur and fog acts as vapor, the addition of fuel fog to the tank ullage in sufficient concentration, .28 lbs. fuel/lb. air (fog plus vapor) completely inerts the tank. The vapor concentration is dictated by the ambient total pressure and the fuel vapor pressure which is dependent only on the fuel temperature. Therefore, the rich limit of flammability is commonly expressed as a particular temperature at some altitude. The fog, acting as a vapor, adds to the vapor pressure concentration effectively lowering the fuel temperature required for the ullage concentration to exceed the rich flammability limit. This depression in temperature has been used to measure the degree of inerting obtained by fuel fogging. The work described in this report was able to demonstrate inerting at a temperature 35°F below the temperature at which natural inerting occurs, that is, the rich flammability limit of JP-4 was dropped from 70°F to 35°F.

The system consists of a fuel fog distribution manifold with fog nozzles located so as to produce a uniform fog distribution throughout the fuel cells under all degrees of ullage and dynamic flight conditions. Since the system uses the fuel itself as the inerting material, no logistic problems are encountered and weight and volume penalties are low.

An Air Force sponsored and funded program under the direction of the Aero Propulsion Fuels Laboratory for development of a working fuel fog system was carried out at the McDonnell Aircraft Division of the McDonnell Douglas Corporation. The program was to be carried out in four phases: (1) to define the fuel fog concentration and distribution with respect to nozzle configuration, grouping, location, and flow rate variations under typical aircraft fuel system operating parameters; (2) to determine the basic limits of flammability of fuel fog under typical aircraft fuel system operating parameters, including constant altitude and changing altitude conditions using electrical and incendiary ignition; (3) the contractor was to provide the Air Force Aero Propulsion Laboratory with six gunfire test tanks, fuel

fogging equipment with instrumentation, and engineering consultation for the FAA Atlantic City facilities; (4) complete operational fuel tank requirements for an F-4C aircraft were to be established, analysed, and compared with current candidate fire and explosion suppression systems.

Section II and III detail the results and conclusions of Phase I and II of the AF funded program. Phases III and IV were terminated prior to contract completion due to the limited degree of success obtained in the inerting capabilities of the fog system. JP-4 ignition tests showed a maximum obtainable fog concentration of 0.14 lb. fuel/lb. air whereas calculations showed that a mass fuel to air ratio of about 0.28 would be required to inert JP-4 over its complete temperature range down to -65°F. Included in this report as Section IV are the results and conclusions of the MDC funded supplementary program. Of significance is the fact that pneumatic devices, no matter what their fuel to air ratio, are not as effective as hydraulic nozzles in fuel fog inerting.

SECTION II

PHASE I CONCENTRATION AND DISTRIBUTION ANALYSIS

1. Visualization Chamber

A visualization chamber and flow system was designed and constructed in Phase I of the program and is shown in Figure 1. This set up was used in all Phase I testing of fog concentration and distribution studies. The chamber consists of a 30" x 30" x 24" steel frame with 2½" thick plexiglass windows on all four sides. The dimensions of the chamber were selected to simulate the standard test fuel cell (MIL-5578) that was to be used in the Phase III gunfire test program. Plumbing fixtures, an access port and a recompression vent were incorporated in the top of the chamber. The chamber was designed to operate with up to 95% ullage over the temperature range of -30°F to 130°F and a pressure range of 5 to 35 psia. Three of the chamber windows were permanently sealed, the fourth was gasketed for access. The chamber was proof pressure tested to 40 psig. Operation of the chamber included a nitrogen pad for safety. The fuel temperature conditioning heat exchanger was mounted adjacent to the chamber as was the pump. The complete set-up was mounted on a wheeled dolly for freedom of transport. A schematic of the flow system for the visualization chamber is shown in Figure 2.

In the initial tests performed in the chamber, it was concluded qualitatively that uniform fog distribution was no problem in that observations of the fog showed it to be highly turbulent. Further, the photo electric cell light transmission monitor indicated a uniform fog distribution even during repressurization cycles.

Other observations of the fog dynamics in the visualization chamber showed that no surface turbulence or foaming resulted from fog impingement on the liquid surface and that the fog produced would not migrate vertically through a two inch open stand pipe placed on top of the fog chamber for sampling purposes.

2. Analytical Methods

Several techniques for sampling the fog were employed. These included a syringe with variations in the suction hole diameter, a particle capture type device and a two liter vacuum botttle. In the first sampling attempts a glass syringe was used, being inserted into the fog chamber in a horizontal orientation and the sample drawn in. This technique gave results of a somewhat questionable nature in that ignition tests carried out with the same nozzles and conditions showed inerting capabilities to a degree commensurate with a higher vapor concentration than that indicated with the sample. In order to improve upon this, samples were taken where the syringe was inserted into the chamber so that the sample was drawn in the direction of natural fall out of the particles. Data obtained in this manner was similar to the previous concentration readings. Plastic syringes in which the suction holes were made larger were then used. With these devices somewhat higher values for concentration were obtained, but not what was anticipated. A device was then built that was designed to capture the falling particles. It was constructed of 3 inch diameter by 3 inch length plexiglass tubing with teflon covers at each end. This device, open at both ends, was inserted into the fog immediately after the fog nozzles were shut off. After three to four seconds, the covers were closed and the device removed from the chamber. Samples taken with

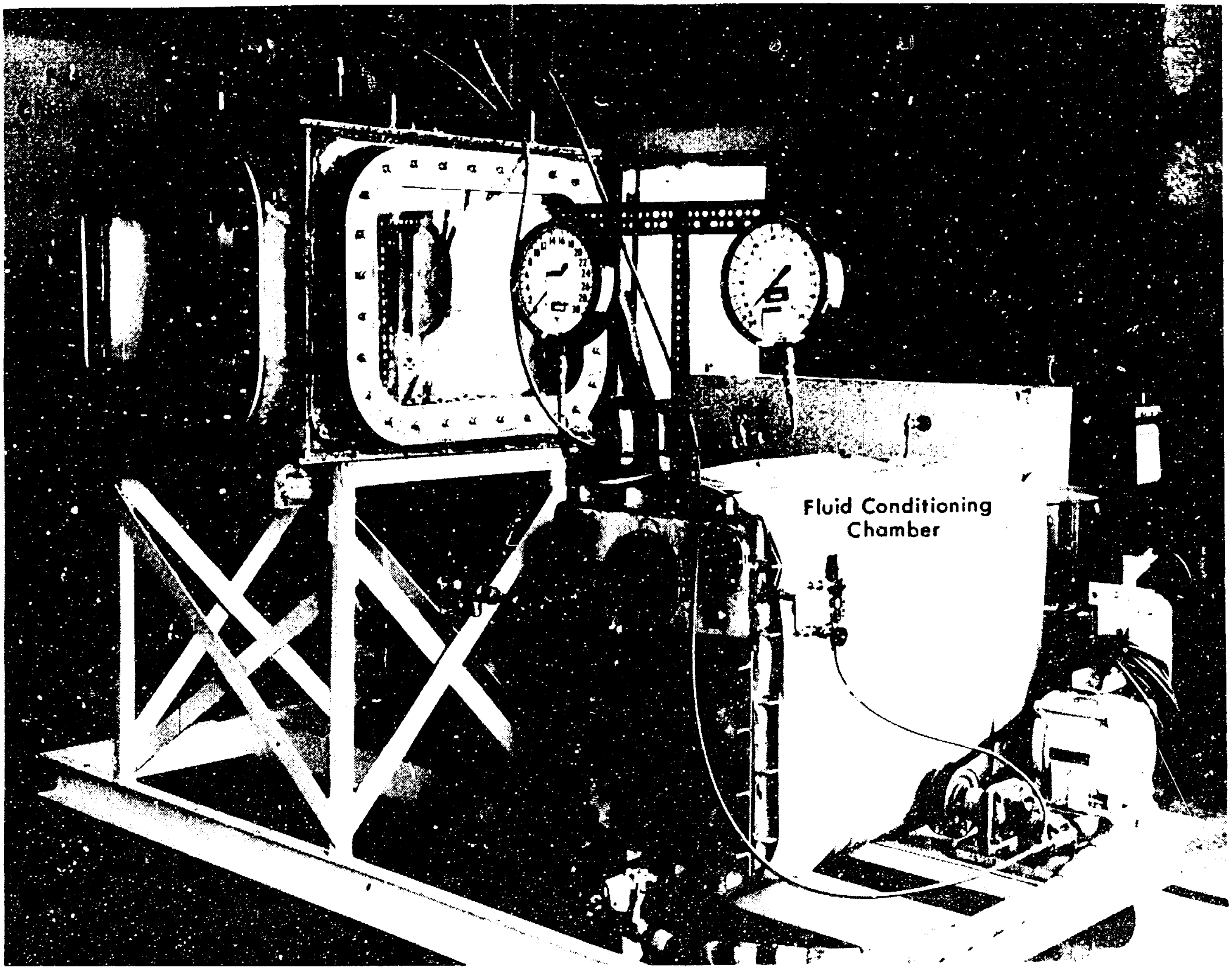


Figure 1
Visualization Chamber Test System

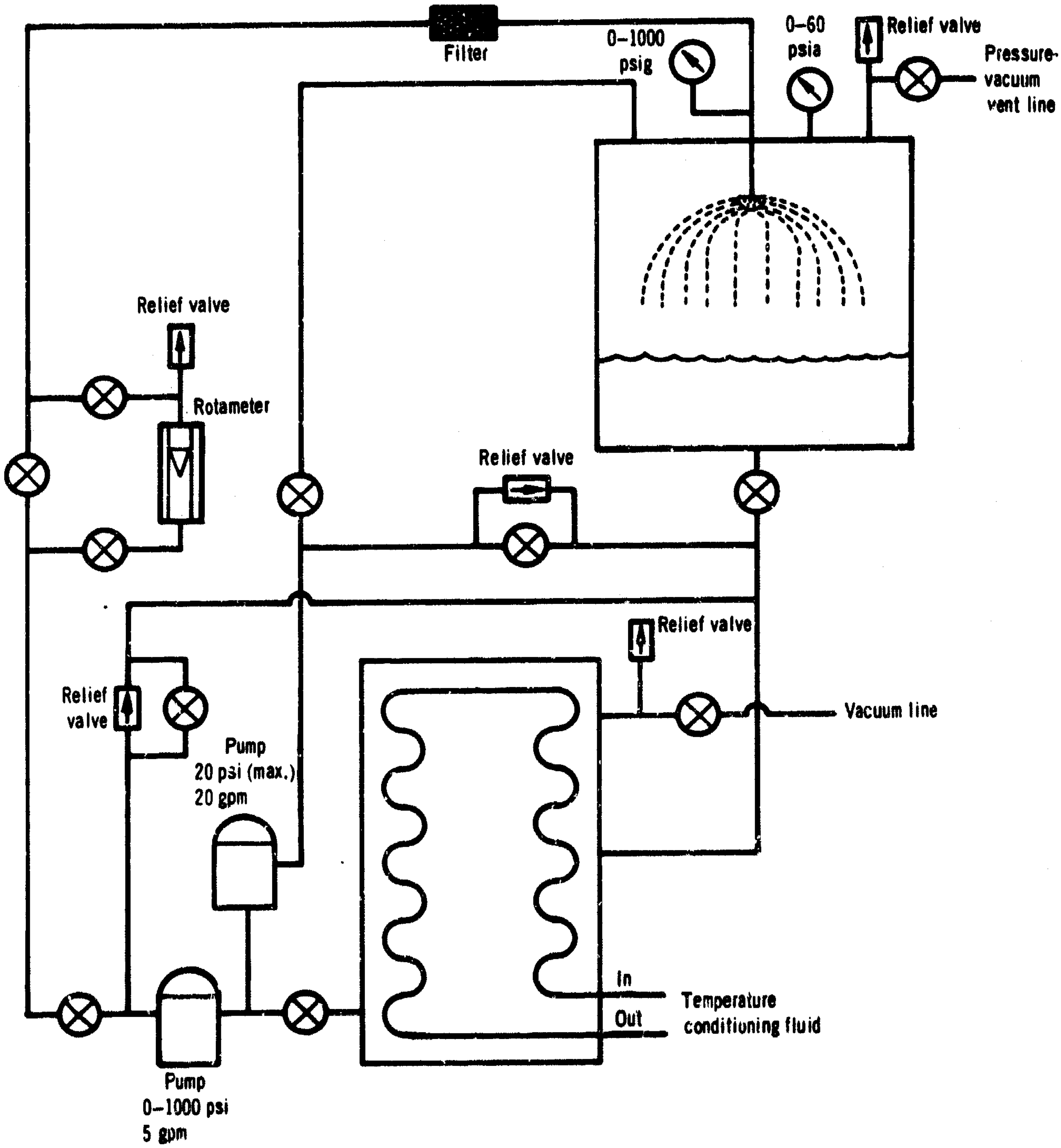


Figure 2 – Fuel Fog Visualization Chamber Flow Schematic

this device averaged slightly higher than with the syringe. Sampling with the vacuum bottle evacuated to 40 mm Hg was done by inserting a teflon tube connected to the vacuum bottle, into the chamber and opening the stop cock valve in the teflon line. The average values of the data taken in this manner were lower on the average than those taken by either the syringe or the capture device.

All samples with the exception of a few, were taken after the fog had been shut off. The concentration data as well as the specific times are recorded in Table 1. The large part of the data taken gave fog concentration readings comparable in magnitude to that of the natural vapor concentrations at that temperature without fog. Natural vapor concentration samples taken and recorded in Table 1 verify this point. In subsequent ignition testing where the ignition source was initiated four seconds after the fog was shut off, in order to duplicate sampling conditions, it was shown that some degree of inerting due to fog enriched vapor was still in evidence. This data tends to negate the concentration measurements where the readings were approximately equal to the natural vapor concentrations. It may also be concluded from this data that particles larger than those remaining in suspension four seconds after the fog nozzles are turned off (50 microns and larger based on particle settling rate in air) play an important role in the inerting capability of the fog. Large variations in concentration were recorded when samples were taken with the fog on. This data scatter was caused by the high degree of turtulence and the drenching of the sampler. Coalesed droplets would form on the sampler and would be drawn in when the sample was taken.

In the small volumes of the samples taken one coalesed droplet of liquid taken into the sampling device would alter the concentration of the sample considerably. This is apparent in that the sampling results showed concentrations on the order of one magnitude greater than those taken at a later date but under similar conditions of types of nozzles and arrangements. Droplets, formed on the syringe tip by coalescence of the falling fog particles were drawn into the sample thus upsetting the results. In the latter tests of the same type where the results were more in line with the majority of the tests, the droplets on the syringe tip were shaken off prior to the drawing of the sample.

The analytical procedure used for all samples includes vapor/liquid cromatography and infra-red spectrography. After a measured sample of fog was drawn, a known quantity of spectrographic grade carbon tetrachloride was placed in with the sample. The sample container was then thoroughly shaken. A sample of the carbon tetrachloride was then analyzed using a Beckman IR-7 spectrograph. The adsorption reading at 3.4 microns was then compared to a previously determined calibration curve giving the milligrams of fuel to milligrams of carbon tetrachloride. Tests with completely vaporized fuel samples showed a 90% recovery of fuel vapor with the carbon tetrachloride adsorption method. All of the liquid droplets that were drawn into the sampler were captured by this method. The vapor remaining in the sampler after the extraction was introduced into a Perkin-Elmer gas chromatography unit and was analyzed for oxygen content. With these results the concentration of fuel to air in the initial sample was calculated. This data is presented in its entirety in Table I.

TABLE I

FOG SAMPLING DATA

NO. OF SAMPLES	NOZZLES TESTED	FUEL USED	TEMP OF TEST	SAMPLING TECHNIQUE	mg. FUEL	mg. FUEL / mg. AIR	CONDITIONS OF SAMPLING
1	1 PT-5 (500 psig)	JP-4	77°	Syringe	6.54	.136	Sampled with nozzles on
2					9.73	.197	
3					8.22	.166	
4					8.78	.158	
1	1 PT-5 (500 psig)	JP-5	77°	Syringe	8.45	.176	Sampled with nozzles on
2					7.98	.166	
3					7.82	.163	
1	2 PT-5 (500 psig)	JP-5	95°	Syringe with tube attached	4.30	.103	Sampled after fog off
2					4.46	.106	
3					3.90	.093	
4				Syringe	7.34	.175	
5					7.34	.175	
6					3.43	.114	
1	1 PT-5 (500 psig)	JP-5	147°	Syringe	4.07	.076	After nozzles off
2					8.25	.153	With nozzles on
3					2.87	.053	After nozzles off

TABLE I (cont'd)

FOG SAMPLING DATA

NO. OF SAMPLES	NOZZLES TESTED	FUEL USED	TEMP OF TEST	SAMPLING TECHNIQUE	mg. FUEL	mg. FUEL / mg. AIR	CONDITIONS OF SAMPLING
1	Ultra Sonic Nebulizer	JP-5	77°	Syringe	3.67	.076	Ultrason Nebulizer
2					3.67	.064	#1 Fogging in bag
3					2.87	.056	#2, 3, 4 - from outlet
4					3.98	.083	Line of nebulizer
1	1 PT-5 (500 psig)	JP-4	77°	Syringe	14.00	.249	Sampled after nozzles off
2					11.00	.216	
3					8.75	.168	
4					8.92	.194	After fog settled
1	1 PT-5 (500 psig)	JP-4	77°	Syringe		.14	#1, 3, 5 sampled
2						.25	After fog settled
3						.15	
4						.2[illegible]	#2, 4, 6 sampled
5						.18	After nozzles off
6						.27	
1	1 PT-5 (500 psig)	JP-4	72°	Wide tip syringe	14.40	.305	Sampled after nozzles off
2					24.60	.518	
3					28.40	.600	

TABLE I (cont'd)

FOG SAMPLING DATA

NO. OF SAMPLES	NOZZLES TESTED	FUEL USED	TEMP OF TEST	SAMPLING TECHNIQUE	mg. FUEL	mg. FUEL / mg. AIR	CONDITIONS OF SAMPLING
1	6 PT-10 (500 psig)	JP-4	77°	Syringe	29.8	.631	Sampled with nozzles on
2					50.2	1.060	
3					62.2	1.340	
4	4 PT-10 (500 psig)			Syringe	11.7	.248	Sampled with nozzles on
5					9.1	.193	
6					11.7	.248	
7	4 PT-5 (500 psig)			Syringe	10.0	.212	Sampled with nozzles on
8					9.2	.196	
9					10.3	.219	
1	4 PT-5 (950 psig)	JP-4	-13°	Syringe	5.8	.121	Sampled with nozzles on
2					3.0	.063	
3					3.2	.067	
4				Wide tip syringe	3.7	.077	Sampled with nozzles on
5					3.3	.068	
6					3.3	.068	
1	7 PT-5 1 PT 10 (500 psig)	JP-4	67°	Syringe	10.25	.216	Sampled with nozzles on
2					10.10	.213	

TABLE I (cont'd)

FOG SAMPLING DATA

NO. OF SAMPLES	NOZZLES TESTED	FUEL USED	TEMP OF TEST	SAMPLING TECHNIQUE	mg. FUEL	mg. FUEL / mg. AIR	CONDITIONS OF SAMPLING
3	7 PT-5 1 PT-10	JP-4	67°	Syringe	12.00	.254	Sampled with nozzles on
4	6 PT-10 (500 psig)	JP-4	67°	Syringe	11.60	.245	Sampled with nozzles on
5					24.15	.510	
6					17.00	.359	
1	6 PT-10 (500 psig)	JP-4	82°	Syringe	10.4	.221	Sampled 4 sec.
2					10.0	.212	After nozzles off
3					15.6	.331	
4					13.4	.285	
5					10.7	.227	Sampled 6 sec.
6					12.3	.261	After nozzles off
7					11.7	.240	
8					13.7	.291	
9					10.0	.212	Vapor Pressure
1	5 PT-5 & 1 PT-10 (500 psig)	JP-4	78°	Syringe	8.9	.188	Sampled nozzles on
2					13.0	.275	
3					24.5	.515	
4					10.4	.220	Sampled 4 sec.
5					9.7	.206	After nozzles off
6					27.9	.590	

TABLE I (cont'd)

FOG SAMPLING DATA

NO. OF SAMPLES	NOZZLES TESTED	FUEL USED	TEMP OF TEST	SAMPLING TECHNIQUE	mg. FUEL	mg. FUEL / mg. AIR	CONDITIONS OF SAMPLING
7	5 PT-5 & 1 PT-10 (500 psig)	JP-4	78°	Syringe	43.7	.925	Sample 4 sec. after nozzles off
8					14.2	.301	
9					14.1	.298	Vapor Pressure
1	6 PT-5 & 2 PT-10 (500 psig)	JP-4	75°	3x3 cycl. device	116.5	.285	Sampled 8 sec. after nozzles off - opened for 3 sec.
2					93.7	.231	
3					93.7	.231	
4					110.0	.271	
5					100.5	.259	
1	5 PT-5 & 3 PT-10 (900 psig)	JP-4	80°	Syringe	8.9	.189	Vapor Pressure
2				3x3 cycl. Device	61.0	.150	
3				"	93.4	.228	Sampled 4 sec. after nozzles off
4				"	106.5	.262	
5				"	89.2	.220	
6				Syringe	9.0	.191	Sampled 4 sec. after nozzles off
7				"	12.3	.252	
8				"	8.2	.233	

TABLE I (cont'd)

FOG SAMPLING DATA

NO. OF SAMPLES	NOZZLES TESTED	FUEL USED	TEMP OF TEST	SAMPLING TECHNIQUE	mg. FUEL	mg. FUEL / mg. AIR	CONDITIONS OF SAMPLING
1	5 PT 5 & 3 PT 10 (500 psig)	JP-4	71°	3x3 Cycl. Device	72.2	.176	Sampled 6 sec. after nozzles off
2					82.8	.202	
3					92.3	.226	
4					71.7	.175	
5					83.6	.204	
6					77.2	.189	
7				Syringe	5.46	.115	Sampled 6 sec. after nozzles off
8					10.4	.220	
9					10.4	.220	
10					9.5	.201	
11					11.4	.241	
12					12.5	.264	
13					9.7	.205	Quick sampling fog on
14					12.7	.269	
15					10.90	.230	Quick sampling fog on
16					17.80	.376	
17					8.75	.186	Vapor Pressure
18					8.20	.174	"

TABLE I (cont'd)

FOG SAMPLING DATA

NO. OF SAMPLES	NOZZLES TESTED	FUEL USED	TEMP OF TEST	SAMPLING TECHNIQUE	mg. FUEL	mg. FUEL / mg. AIR	CONDITIONS OF SAMPLING
1	5 PT 5 & 3 PT 10	JP-4	75°	2L Flask @ 40mm Hg	373.0	.158	Flask @ 40mm Hg
2					378.4	.160	
1	5 PT 5 & 3 PT 10	JP-4	73°	2L Flask @ 40mm Hg	145.5	.062	Flask @ 40mm Hg 15 sec. sampling
2					282.0	.119	
1	5 PT 5 & 3 PT 10	JP-4	72°	2L Flask @ 25 to 40mm Hg	330	.140	Vapor Pressure
2			72°		350	.147	Nozzle Pressure
3					350	.147	100# - sampled
4					350	.142	Nozzles off
5			73°		354	.150	Nozzle Pressure
6					326	.137	300# - sampled
7					384	.162	Nozzles off
8			76°		380	.160	Nozzle pressure
9					350	.148	500# - sampled
10					396	.167	Nozzles off
11			76°		378	.160	Nozzle pressure
12					384	.162	500# - sampled
13					380	.161	Nozzles on

3. Fog Nozzles

Several nozzles as shown in Figures 3 through 11 were evaluated in both the MDC funded ignition studies and the plexiglass visualization chamber. Nozzles tested were of two general types, pneumatic and hydraulic, and are listed with their manufacturers below.

Pneumatic Nozzles	Manufacturer
Paint Spray	Spraying Systems Co.
Ultra Sonic Nebulizer	DeVilbiss Co.
Nebulizer with Vibrating reed	Vapo Products Inc.
Sonic	Sonic Development Corp. of Am.
Una-Spray	Rocketdyne

Hydraulic Nozzles	Manufacturer
Simplex (solid and hollow cone)	Monarch Manufacturing Works
Multi Orifice	Spraying Systems Co.
High pressure	Spraying Systems Co.
Impingement	Bete Fog Nozzle Inc.
Spiral Fog Nozzle	Bete Fog Nozzle Inc.

Pneumatic paint spray nozzles (Figure 3) were used initially because of their availability at the time the MDC ignition set up was to be checked out. This nozzle is supplied with air and fuel, both under pressure, that may be adjusted to change the fuel to air ratio and droplet size. This nozzle proved to be ineffective as an inerting device. The average particle size for this nozzle as reported by the manufacturer was 200 micron.

The Ultra-Sonic Nebulizer was investigated as a possible pneumatic source for producing a high concentration of extremely small fog particles. The nebulizer produces fog by subjecting a liquid surface to high frequency (1,350,000 cycles per second) mechanical vibration. The fog produced in this fashion appeared to be made up of densely packed small particles but in sampling the concentration was relative to that taken with other fog producing nozzles. Particle size for this nozzle as reported by the manufacturer range from 1 to 5 micron. Ignition tests were not run with this nozzle.

The nozzle of the nebulizer type with vibrating reed (Figure 4) operated by pneumatic pressure forcing the fluid stream against a vibrating reed was found to produce a concentration of small particles of 2.75 pounds fuel per pound air. Although the flow ratios measured for this nozzle indicated that the fog concentration was high enough to effect complete inerting, ignition tests showed that the inerting capability was relatively small and in line with other pneumatic nozzles.

The sonic nozzle (Figure 5) with a maximum fuel to air ratio of 1.77 pounds fuel per pound air performed very similar to the nebulizer nozzle above with the exception that the pneumatic supply required is considerably less (14 psi versus 40 psi air). The nozzle expands low pressure supply gas through a supersonic nozzle focusing the resultant pressure wave into an open cavity. The resulting acoustic energy so produced atomizes the fuel that is siphoned into the cavity. This nozzle was extensively tested as an inerting device. Variations in fuel, which will be discussed in a later section, changes in fuel temperature, and air

temperature and pressure were tested with this nozzle. The inerting capability of the nozzle by these methods was not enhanced as evidenced in Table 2 and 3.

The Una-Spray nozzle (Figure 6) was operated by flowing a film of fluid over a hollow sphere containing a slit while pressurized air was flowed into the ball and subsequently out the slit breaking the film into uniform small droplets, thus producing a fog. From visual examination, it appeared that this nozzle produced the most uniform droplet size fog of all those tested although ignition tests (Table 4) proved that this fog was no more effective than those produced by the sonic nozzles. The manufacturer estimated a fuel to air mass ratio for this nozzle of 10 to one which is the highest obtained in the program for a pneumatic nozzle.

The most effective of the pneumatic nozzles was able to suppress the rich flammability zone 15°F for JP-4. Fuel antistatic additives and changes in air pressure and temperatures had no effect on the inerting capability of the nozzle. By using fuel saturated air for the pneumatic supply to the nozzle an additional 4°F in the depression of the rich flammability limit was recorded.

Simplex type hydraulic nozzles (Figure 7) produced fogs of varying degrees depending on the pressure used and the size of the orifice in the nozzle. All simplex nozzles were of a similar type where the fluid is pumped or pressure fed into the nozzle and subsequently through the orifice. Some of these nozzles proved to be no more than spray type devices rather than fog producing nozzles. The quality of the fog was considerably improved by increasing the fuel pressure and decreasing the orifice size, but this is only practical to a certain degree. The orifice size must be such that fuel contamination will be no problem with standard filters and pressure must be compatible to existing aircraft equipment. The smallest orifice used was 0.005 inch diameter with a pressure of 500 psig. Both higher and lower pressures were tried but it was found that increasing the pressure over 500 psig did not alter the fog concentration, consequently the inerting capabilities, in proportion to the pressure rise. Thermal flashing of the JP-4 fuel through the simplex nozzle was investigated in order to determine any change in the inerting effect of the nozzle. Fuel was heated under pressure to 215°F and run through the nozzle causing a flashing of the fluid upon exit. No change in the inerting capability of the nozzle was realized. The degree of inerting with this nozzle (Table 5) was approximately the same as the best pneumatic type nozzle (15°F). Particle diameter and distribution information was not available. Low pressure simplex type nozzles with multi-orifices (Figure 8) did not visually produce sufficient fog to warrant any ignition testing. Flow rates for this nozzle at 150 psi are 0.45 GPM with average particle size as reported by the manufacturer of greater than 200 micron diameter.

The high pressure (7000 psig) hydraulic nozzle (Figure 9) of the simplex type was evaluated with and without impingement plates. Without the impingement plates, the nozzles produced a stable fluid stream of over four feet in length before breaking up into a fine mist. With an impingement plate a fine mist was produced, not a fog as evidenced by immediate settling of the particles upon shutting off the nozzle. Since no fog was produced, ignition tests of this nozzle were not carried out.

Impingement nozzles (Figure 10) where the fluid stream is projected against an impingement plate downstream of the orifice, gave the greatest degree of inerting obtainable on the program. The most effective of this type nozzle has a 0.005 inch

diameter orifice and is operated under a pressure of 500 psig. At these conditions the flowrate for each nozzle is 1.4 gallons per hour with an average particle size as reported by the manufacturer, of 30 microns. The fog produced by this nozzle was effective in lowering the rich limit of flammability of the vapor a total of 35°F (Table 6). This value was repeated under several conditions with a 14 joule ignition source where the number of nozzles was changed in a set volume and the ullage pressure was lowered from ambient. In a container of approximately one cubic foot volume one and two nozzle combinations produced identical inerting results. In a container of 100 gallon capacity 8 nozzles and 16 nozzles, simulated by halving the ullage volume, inerted to within 4°F of the above reported results. By changing the ignition source the total degree of inerting of this system changed; i.e., the higher the energy of the ignition source, the lower the indicated inerting value. Changing the ullage pressure seemed to have no effect on the performance of the nozzle either by visual examination or differential inerting capability with respect to the rich flammability zone under equilibrium conditions.

A pinless spiral hydraulic type nozzle was evaluated as a possible fogging device (Fig. 11). This nozzle is a simplex device with an external spiral mechanism designed to give the exiting fluid stream a swirling motion thus increasing its velocity and furthering droplet breakup. During flow tests with JP-4 this nozzle proved to be no more than a spray nozzle therefore ignition testing was not deemed necessary.

Hydraulic nozzles have been demonstrated to inert approximately twice that attainable with a pneumatic system even though with pneumatics the droplets produced are smaller and fuel to air ratios more than adequate to totally inert the ullage space. The explanation given for this phenomena is the fact that a pneumatic nozzle continuously brings fresh air into the system, thus lowering the vapor concentration in the system and making inerting by the fog an even more difficult task. There is also reason to believe that the droplets formed by pneumatics are simply bubbles of air encapsulated by a film of fuel. When this bubble bursts under the influence of a high energy ignition source, local zones of flammable mixtures are generated and will ignite and propagate through the mixture. Further discussion on the theoretical combustion process of fog is presented in Section III.

4. Capacitance Probe

The capacitance probe, fuel-fog concentration measurement instrument development was completed but no tangible data could be taken. The field effects transistor probe designed and tested for this program proved to be too sensitive to temperature and pressure variations as well as wetting. These variations greatly affected the signal output of the probe, making it impossible to obtain a stable reading. Further, the change in dielectric constant of the sample volume due to the fog concentration resulted in only 324 microfarad capacitance change which is quantitatively less than the present precision measurement capability employed by the National Bureau of Standards. While this result is negative with respect to the capacitance probe development, it indicates that the standard capacitance fuel-gauging system will be unaffected by the fuel fog.

The fog concentration measurement probe was a single plate capacitor type shown in Figure 12. It had an effective plate area of 6.42 square centimeters and a plate separation of 1 centimeter. Three plates were made for the probe. The first plate had a rough face surface and collected excessive amounts of liquid when placed in the fog. The second and third were revisions of the first in that both were polished

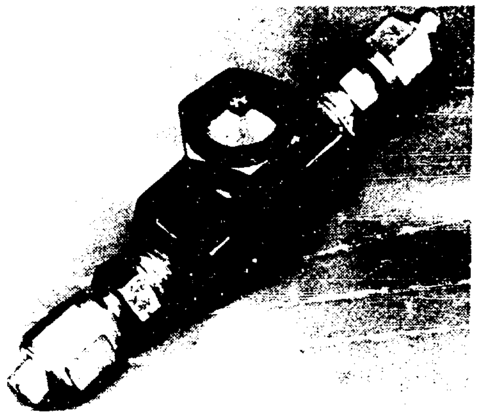


Figure 3
Pneumatic Fog Nozzle

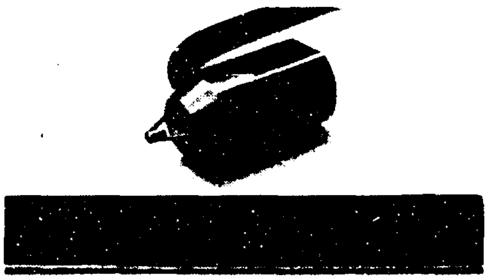


Figure 5
Pneumatic Sonic Nozzle

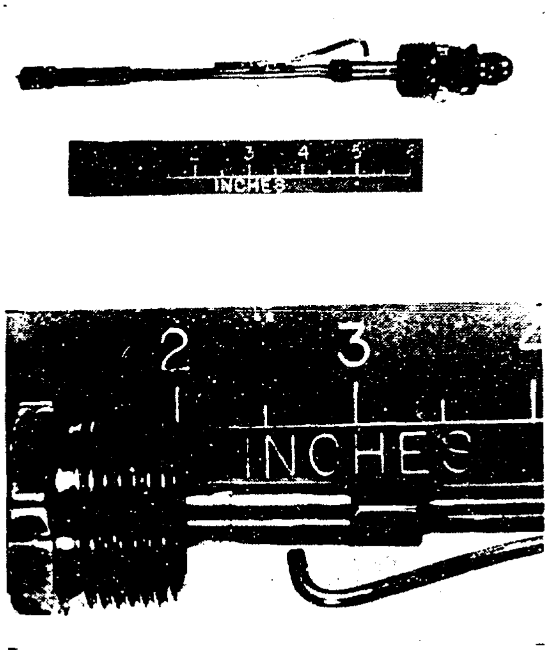
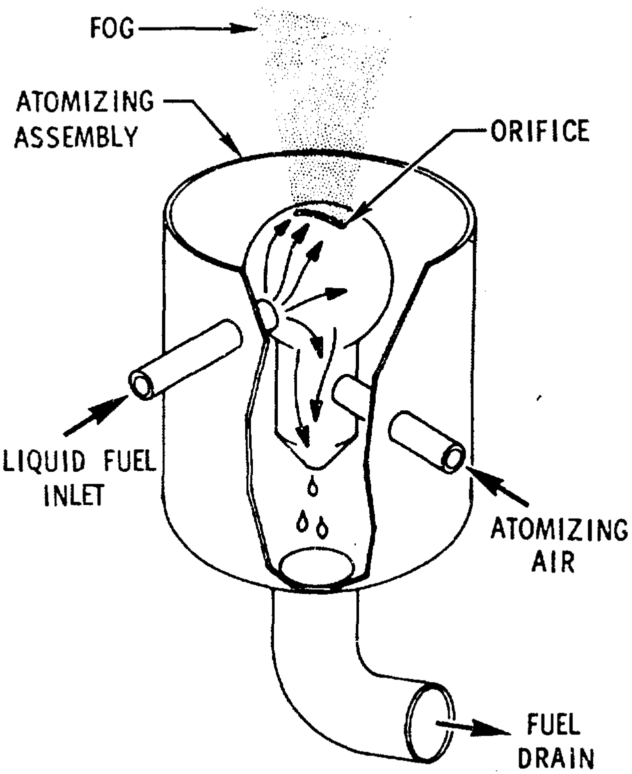


Figure 4
Ultrasonic Nebulizer Nozzle



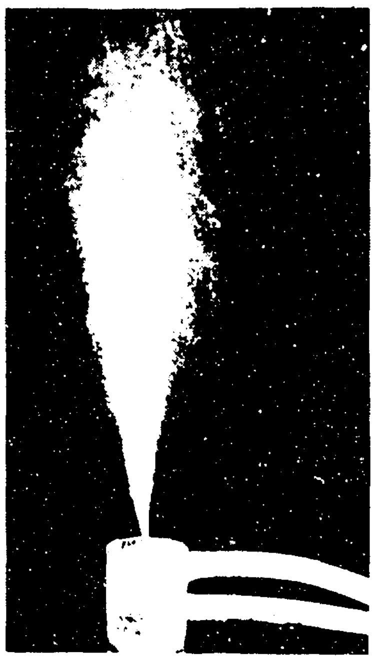


Figure 6
Una-Spray Atomizing Concept

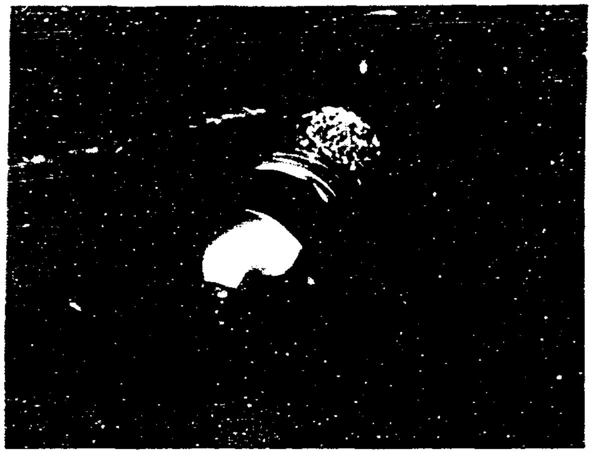


Figure 7
Hydraulic Simplex Nozzle

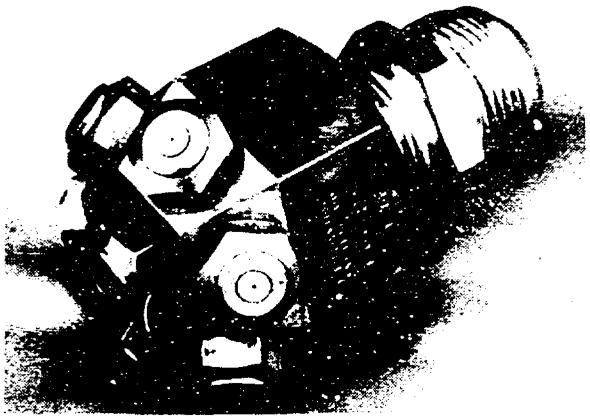


Figure 8
Hydraulic Multiple Orifice Nozzle

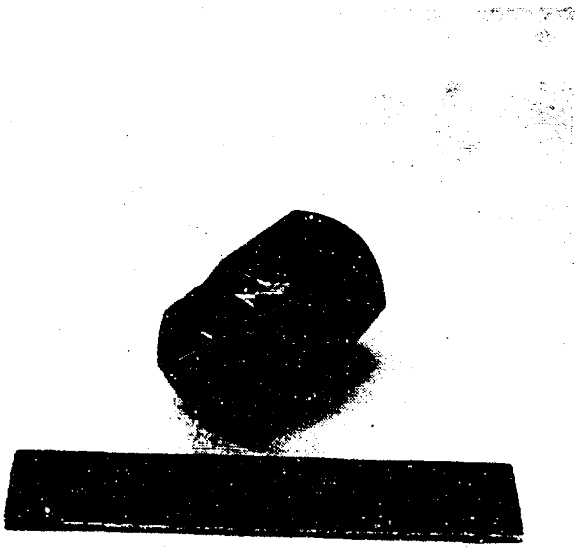


Figure 9
Hydraulic High Pressure

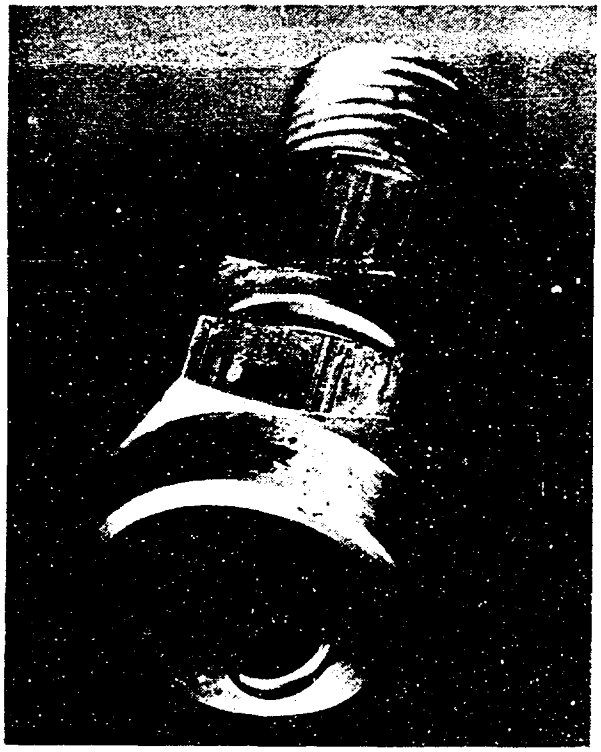


Figure 10
Hydraulic Impingement Type Nozzle

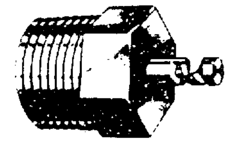


Figure 11 Spiral Fog Nozzle

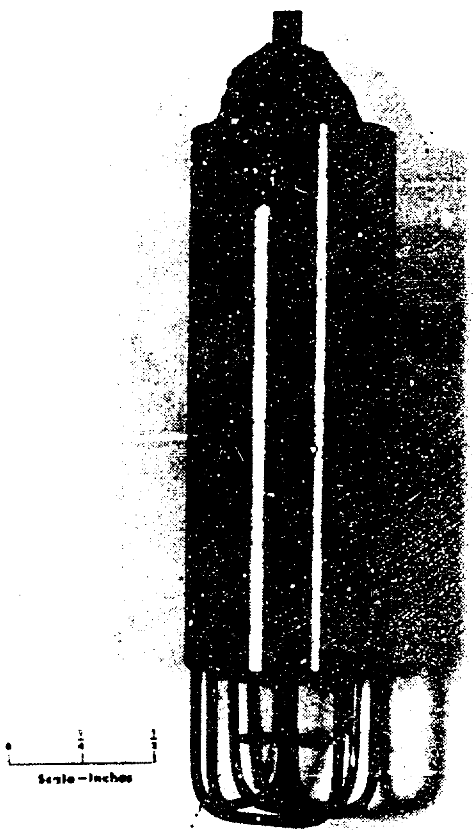


Figure 12 Multiphase Capacitance Probe

TABLE 2

SONIC NOZZLE - JP-4 FUEL

FRESH SHOP AIR USED AS PNEUMATIC SUPPLY

RUN NO.	NOZZLE AIR PRESS (PSIG)	NOZZLE AIR TEMP (°F)	FUEL WATER BATH TEMP. (°F)	FLOW DURATION PRIOR TO IGNITOR ACTUATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITOR ACTUATION	REMARKS
1	14	70	60	3	56	On	No Fire
2	14	70	60	4	56	On	No Fire
3	14	70	60	5	56	On	Fire
PNEUMATIC SUPPLY SATURATED WITH JP-4 VAPOR							
4	14	72	60	3	58	On	No Fire
5	14	72	60	4	58	On	No Fire
6	14	72	60	5	58	On	No Fire
7	14	72	46	3	54	On	No Fire
8	14	72	46	4	54	On	No Fire
9	14	72	46	5	53	On	No Fire
10	14	72	44	6	52	On	No Fire
11	20	72	44	7	52	On	Fire
12	14	70	35	9	52	On	No Fire
13	14	70	36	12	52	On	Fire
14	10	70	38	4	58	On	No Fire
15	10	70	38	5	56	On	No Fire
16	10	70	36	6	55	On	No Fire
17	10	70	32	7	54	On	No Fire

TABLE 3

SONIC NOZZLE - JP-4 FUEL WITH ANTI-STATIC ADDITIVE

0.001 Gram Anti-Static Additive Per Liter JP-4							
RUN NO.	NOZZLE AIR PRESS (PSIG)	NOZZLE AIR TEMP (°F)	FUEL WATER BATH TEMP. (°F)	FLOW DURATION PRIOR TO IGNITOR ACTUATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITOR ACTUATION	REMARKS
1	14	153	60	2	55	On	Fire
2	14	180	60	2	60	On	Fire
3	14	210	60	1.5	62	On	Fire

TABLE 4

ROCKETDYNE UNA-SPRAY NOZZLE - JP-4 FUEL

FRESH SHOP AIR USED AS PNEUMATIC SUPPLY						
RUN NO.	NOZZLE AIR PRESS (PSIG)	NOZZLE AIR TEMP. (°F)	FLOW DURATION PRIOR TO IGNITION ACTUATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITION ACTUATION	REMARKS
1	10	70	2	58	On	Fire
2	10	70	2	54	On	No Fire
3	10	70	2	50	On	Fire
4	15	70	2	50	On	Fire

TABLE 5

HYDRAULIC NOZZLE - PLASTIC BAG TYPE IGNITION CHAMBER
(SIMPLEX TYPE)

FUEL	FUEL PRESSURE (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITOR ACTIVATION (MIN)	FOG TEMP (°F)	CELL TEMP (°F)	FOG CONDITION AT IGNITOR ACTIVATION	REMARKS
JP-4	500	83	3	50	79	On	Fire
JP-4	300	83	3	50	79	On	Fire
JP-4	300	83	3	30	79	On	Fire
JP-4	500	82	3	78	82	On	Fire
JP-4	500	78	0.166	80	86	Off	Fire 8 Minutes After Fog Turned Off Sparking Every 10 Sec.
JP-4	300	60	2	65	70	On	No Fire
JP-4	500	58	3	63	70	On	Fire
JP-4	300	58	2	63	70	On	Self Extinguishing Fire
JP-4	500	55	3	65	70	On	Fire
JP-4	300	52	2	65	70	On	No Fire
JP-4	300	50	2	65	70	On	No Fire
JP-4	200	50	1.5	63	70	On	Fire
JP-4	150	50	2	65	70	On	No Fire
JP-4	300	226	8	50	91	On	Fire
JP-4	300	215	8	70	91	On	Fire

TABLE 5 (CONTINUED)

FUEL	FUEL PRESSURE (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITOR ACTIVATION (MIN)	FOG TEMP (°F)	CELL TEMP (°F)	FOG CONDITION AT IGNITOR ACTIVATION	REMARKS
IGNITION TESTS CONDUCTED IN RIGID EXPLOSION PROOF IGNITION CHAMBER							
JP-5	300	90	1	90	90	On	Fire
JP-5	400	90	1	90	90	On	Fire
JP-5	500	90	1	90	90	On	Fire
JP-5	600	90	1	90	90	On	Fire
JP-5	780	90	1	90	90	On	Fire
JP-4	500	90	1	90	90	On	No Fire

TABLE 6

HYDRAULIC NOZZLE - PLASTIC BAG TYPE IGNITION CHAMBER (IMPINGEMENT TYPE)

FUEL	FUEL PRESSURE (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITOR ACTIVATION (MIN)	FOG TEMP (°F)	CELL TEMP (°F)	FOG CONDITION AT IGNITOR ACTIVATION	REMARKS
JP-4	300	208	Flow Until Fog Temp. Stabilizes	55	91	On	0.005 Diameter Orifice Nozzle
JP-4	300	204	Flow Until Fog Temp. Stabilizes	52	91	On	Fire
JP-4	300	217	Flow Until Fog Temp. Stabilizes	45	91	On	Fire
JET-A	480	92	1	94	92	On	Fire
JET-A	480	210	Flow Until Fog Temp. Stabilizes	142	92	On	Fire
JET-A	300	98	1	96	88	On	Fire
JP-5	300	300	Flow Until Fog Temp. Stabilizes	142	90	On	Fire
JP-5	300	91	1	91	91	On	Fire
JP-5	500	91	1	91	91	On	Fire
JP-5	700	91	1	91	91	On	Fire
JP-5	500	90	1	90	90	Off	Ignited 3 Sec. After Flow Termination With Continuous Spark.

TABLE 6 (CONTINUED)

FUEL	FUEL PRESSURE (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITOR ACTIVATION (MIN)	FOG TEMP (°F)	CELL TEMP (°F)	FOG CONDITION AT IGNITOR ACTIVATION	REMARKS
IGNITION TESTS CONDUCTED IN RIGID EXPLOSION PROOF IGNITION CHAMBER							
*JP-4	500	75	1	52	75	On	No Fire
*JP-4	500	75	1	52	75	Off	Spark Every 5 Sec - Fire After 25 Seconds
*JP-4	500	75	1	48	75	On	No Fire
*JP-4	500	75	1	45	75	On	No Fire
*JP-4	500	75	1	41	75	On	No Fire
*JP-4	500	75	1	34	75	On	No Fire
*JP-4	500	75	1	30	75	On	Fire After 15 Sec Continuous Sparking
*JP-4	500	75	1	25	75	On	Fire After 0.4 Sec Continuous Sparking
*JP-4	500	75	1	21	75	On	Fire - 100 psi Surge Pressure
*JP-4	500	75	1	34	75	Off	Activate Ignitor Every 5 Seconds - Fire in 15 Sec. 48 psig Surge Pressure.

*Tests in Rigid Explosion Chamber were repeated using same type nozzle but with 0.010 diameter orifice. Data gave results of a similar magnitude.

surface plates, one coated with teflon. These revisions were intended to minimize the film of liquid collected by the plate. Even with these measures, the film collected was far in excess of any fog that would pass between the plate and the grid work, thereby, negating the fog concentration reading entirely.

Other measuring techniques were investigated. These include radioactive, spectroscopic, photoelectric, ultrasonic, and microwave methods. It was concluded from this study that gamma radiation, photoelectric and microwave systems may be sensitive enough to make the desired measurements, but R & D beyond the scope of the program would be involved.

A photoelectric cell system was nevertheless set up to monitor the fog concentration. Calibration of the instrument was not attempted due to the lack of standards and the unknown particle size distribution, which greatly affect the degree of light scattering and transmission. The photoelectric cell monitoring system proved quite useful on a comparative basis in determining the optimum operating pressure for the nozzles tested. Figure 13 shows the typical light absorption curves obtained for the Bete PT-5 nozzles at various operating pressures. The flat portion of the curves left of zero on the time scale is indicative of the fog concentration with the nozzles operating. To the right of zero time is the settling curve, the slope of which is indicative of the population of fine droplets as indicated by the settling rate. From this figure, it appears that 500 psig operating pressure is optimum for these nozzles which, in fact, was confirmed by later ignition studies. Increasing the number of nozzles or reducing the volume per nozzle had no effect on the indicated peak or maximum concentration obtained.

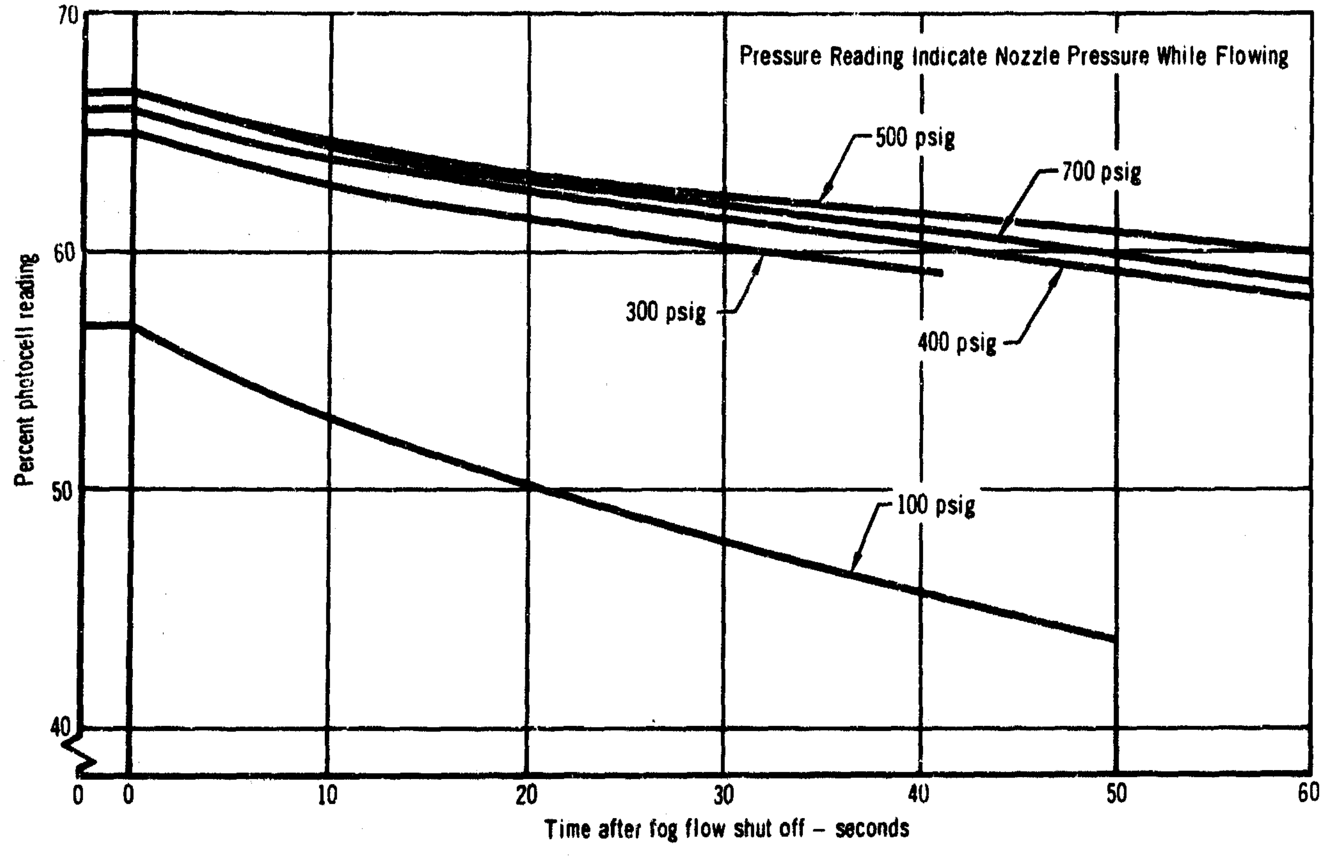


Figure 13
Photocell Reading of Light Absorption after Fog Flow Shutoff

SECTION III

PHASE II (IGNITION STUDIES)

1. Explosion Chamber

The program ignition studies were carried out in a combination explosion and vacuum chamber (Figure 14) containing a 30" x 30" x 24" fuel cell constructed from 0.050 inch aluminum plate. This fuel cell (Figure 15) was designed and sized to simulate a standard MIL 5578 100 gallon aircraft fuel cell. Plexiglass windows were placed in three sides of the cell for visual observation, lighting and blow out protection in case of explosion. The upper side of the cell consists of hinged light weight doors designed for pressure release in case of fire or explosion. The cell, containing the fog nozzles to be verified (Figure 16) was placed in the explosion chamber (Figure 17) and the various ignition sources initiated. During testing in this manner, the cell sustained major damage in one instance (Figure 18 and 19) and a redesign was made to prevent recurrence. The damage was sustained by an external explosion relative to the fuel cell, but internal to the explosion chamber. As the ignition source ignited the fog vapor, the pressure rise in the fuel cell forced the upper lids open thus spewing burning and unburned fuel fog into the fresh oxygen supply exterior to the fuel cell. Note that while one wall of the fuel cell is blown out, all plexiglass view ports are shattered and are contained in the cell. Subsequent revisions to eliminate this damage in the future included removal of large percentage of the front face of the cell and replacing it with plastic sheet, and taping the plexiglass windows rather than permanently affixing them to the inside of the cell.

Temperature instrumentation included thermocouples located outside the chamber for ambient temperature readings, inside the explosion chamber but exterior to the fuel cell, the top and bottom surface of the fuel cell, in the liquid fuel supply at the nozzle manifold and three equally spaced from top to bottom in the fuel cell for recording fog temperature. Pressure instrumentation included a 0 to 1000 psi gauge upstream of the nozzle manifold, a 0 to 100,000 foot altitude gauge on the explosion chamber, a 0 to 30 inch Mercury vacuum gauge mounted on the explosion chamber and read out on an oscillograph recorder. The fluid flow was monitored with a turbine flowmeter and read out on a digital totalizer.

2. Ignition Studies

Hydraulic impingement type nozzles were used in all ignition testing because of their proven inerting ability and performance superiority over other nozzles in the production of fog. These nozzles were tried with various orifice sizes and combinations, all arrangements in a diagonal pattern in the chamber. The Bete PT-5 proved to be the most effective from an inerting standpoint of the impingement nozzles tested.

Ignition studies were carried out using three ignition sources; two electrical spark ignitors (Table 7 and 8) and an incendiary compound (Table 9) manufactured by U.S. Flare consisting of a magnesium base silastic bonded compound. The spark ignitors were of two types, one a capacitance spark of 14 joule energy while the second was an inductance spark of 0.1 second duration 10,000 volts, 23 milliamp and

23 joule energy. The incendiary was used in quantities of 2 gram pellets with an energy equivalent to 1330 calories/gram, thus simulating the .50 caliber A.P.I. projectile (Figures 20 and 21). Flammability limits were plotted for all three ignition sources to 5.5 psia (25,000 ft. altitude) and are shown in Figures 22, 23 and 24. At 3 psia (38,000 ft. altitude) ignition tests were run with the capacitance spark device but no definite limit of flammability could be found. Cool flames were observed at the higher temperatures (20 to 40°F) at this altitude and always associated with a high pressure rise. It is interesting to note that the rich flammability limits of JP-4 under dynamic fog conditions using the two electrical ignitors are parallel lines on the graphs with their separation dependent upon the energy of the ignition source. Incendiary, however, acts quite differently. At sea level the flammability limit using an incendiary seems to be out of perspective in accordance with the limits established at altitude. At altitudes of 10,000, 19,000 and 25,000 feet the flammable limit established with incendiaries lies on the same points as the flammable limit determined by the 23 joule electrical ignitor while at sea level the limit with incendiaries is far removed from that of the 23 joule ignitor. This sea level limit with incendiaries was initially in doubt and was therefore run again three weeks after the first test. The initial results were verified. It would seem from this data that the incendiary is limited in its inherent oxygen supply and is therefore dependent on an external supply of oxygen to completely burn. In this case, at sea level the incendiary will oxidize completely thus releasing its entire energy into the ullage whereas the lack of oxygen at higher altitudes would limit the oxidation and thus the energy release. It was also determined that the equilibrium vapor rich flammability limit varies with the energy of the ignition source. This phenomena with respect to electrical ignitions is caused by heat and mass transfer in the fog or vapor. At the ignition source initiation the heat energy released increases, locally, the temperature of the surrounding media. For a small energy source, the heat released is transferred to the vapor or fog droplets and dissipated with a slight temperature rise in the heat sink. As the thermal energy released is increased, this local temperature rise also increases until the autoignition temperature of the fluid particles is reached, whereby the vapor ignites and propagation occurs as described in the original ignition phenomena. This theory is somewhat borne out in the testing program where ignition occurred in some instances on the third spark when the system was slightly on the rich side of the established flammable zone. From this data it is surmised that the heat generated by the first two sparks warmed the system locally to the point where heat added from the third spark was sufficient to raise, the mixture locally to the autoignition temperature, thus ignition occurred.

With high energy ignition sources such as the 23 joule electrical ignitor and the incendiary, it appeared from the data that little or no inerting due to fog was taking place. In order to investigate this, a series of vapor flammability tests were run with the different ignition sources. These tests were run by spraying fog into the fuel chamber for three minutes, while the lids and windows were taped shut; waiting one hour and initiating the ignitor source. It was shown that at sea level, the equilibrium flammability zone was shifted to a somewhat higher temperature, this shift once again dependent upon the energy of the ignition source. From this it can be shown that the differential between the vapor equilibrium and the dynamic fog flammable limit remain essentially constant but shifted up the temperature scale, this shift of the two limits dependent upon the energy of the ignition source. The shift of the equilibrium curve will only go to the point where true rich limit is obtained. At sea level conditions the erratic results using incendiary ignition sources prevented us from reaching this true limit. At altitude this limit was obtained by both the incendiary and 23 joule ignition source. These results seem to add credence to the use of the 23 joule ignition source as the required energy level necessary to establish true flammability limits.

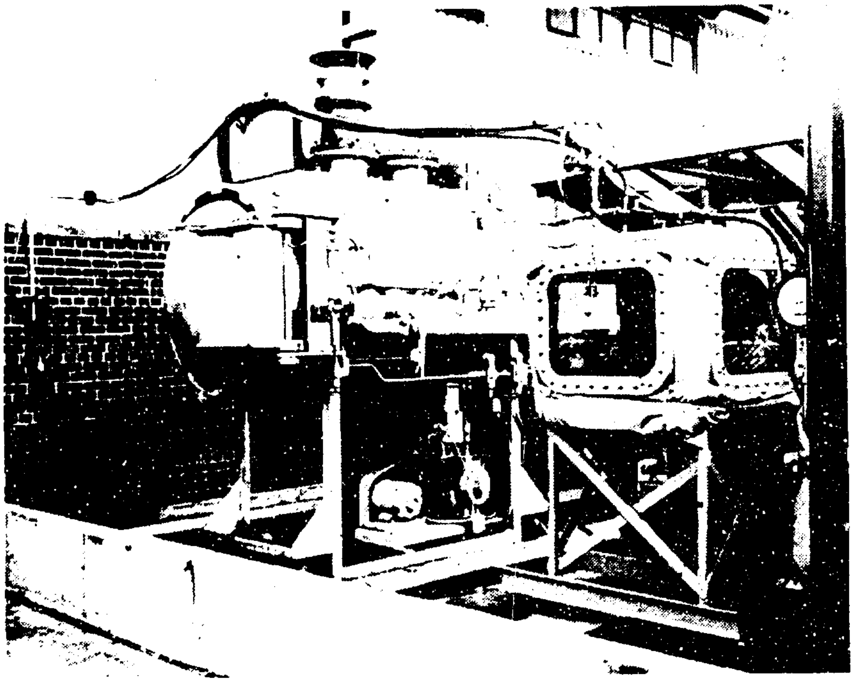


Figure 14
Phase II Explosion Chamber Set-Up

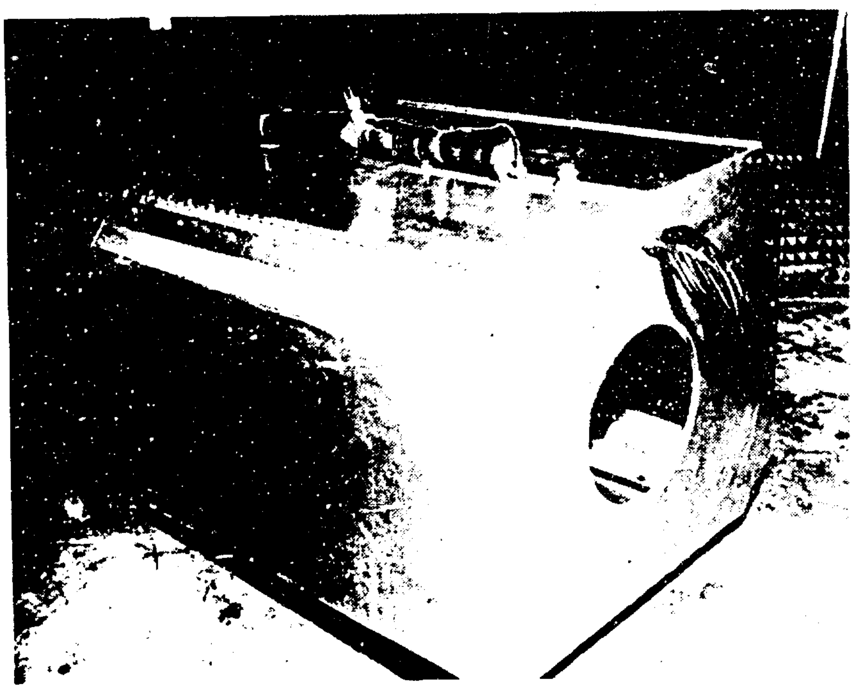


Figure 15
Fuel Cell for Ignition Studies

Figure 16
Fuel Cell with Top Open Showing Nozzle Location

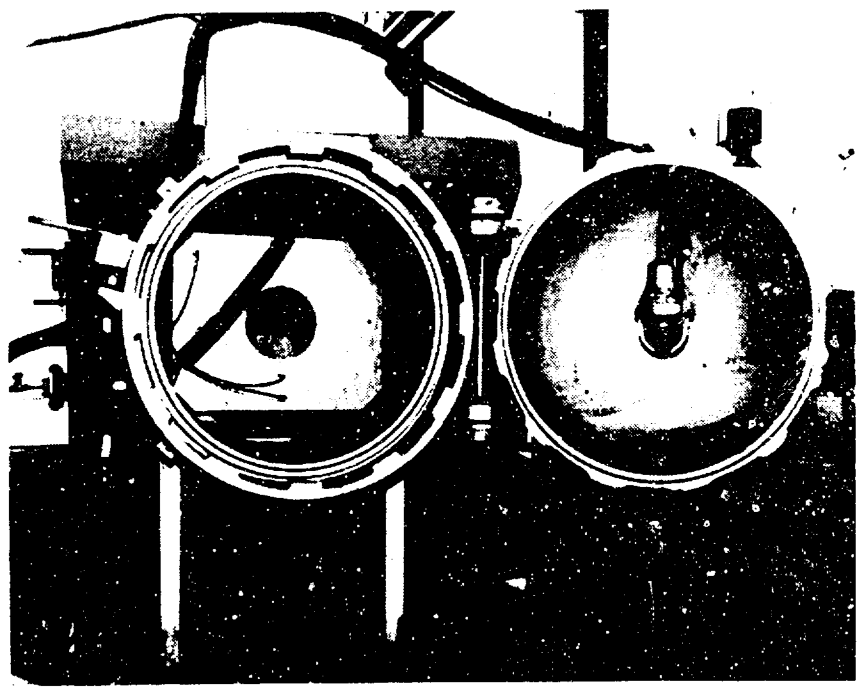


Figure 17
Fuel Cell Inserted in Explosion Chamber

Figure 18
Damaged Fuel Cell Exterior

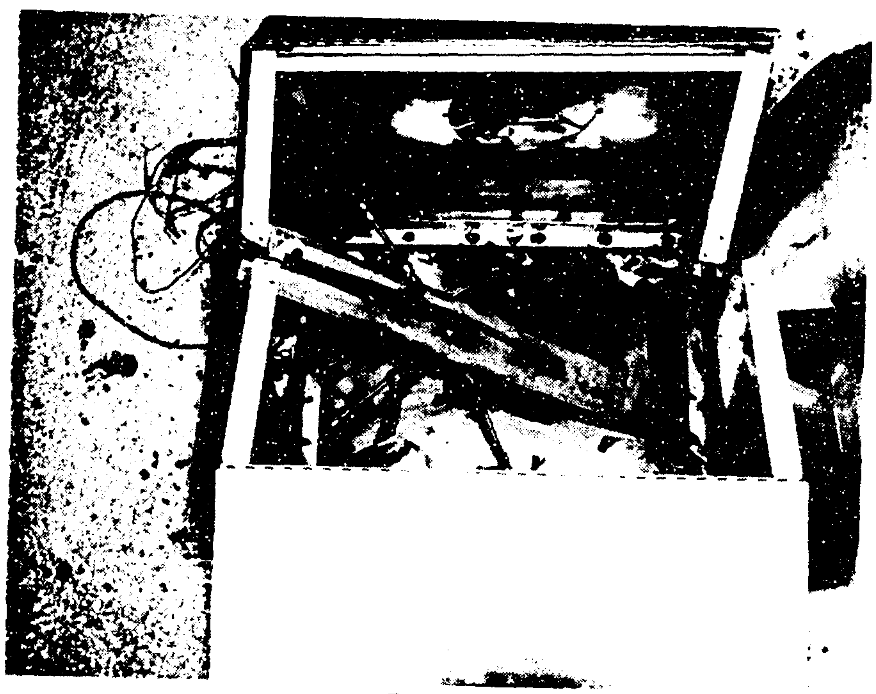


Figure 19
Damaged Fuel Cell Interior

TABLE 7

IMPINGEMENT TYPE NOZZLE - 8 NOZZLES IN SIMULATED FUEL CELL -
DIAGONAL NOZZLE ARRANGEMENT - CAPACITANCE SPARK 14 JOULE - JP-4 FUEL

RUN NO.	ABSOLUTE PRESS (PSIA)	FUEL PRESS (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITION ACTUATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITOR ACTUATOR	REMARKS
1	AMB	500	52	5	40	On	Fire
2	AMB	500	45	5	43	On	Fire
3	AMB	500	38	5	45	On	No Fire
4	AMB	500	50	5	48	On	No Fire
5	AMB	500	52	5	50	On	No Fire
7	10	500	21	5	18	On	Fire
8	10	500	30	5	28	On	Fire
9	10	500	24	5	28	On	Fire
10	10	500	30	5	33	On	No Fire
11	10	500	39	5	39	On	No Fire
12	7	500	7	5	11	On	Fire
13	7	500	14	5	16	On	Fire
14	7	500	13.5	5	17.5	On	Fire
15	7	500	19	5	20	On	No Fire
16	7	500	22	5	24	On	No Fire
17	5.5	500	19	5	3	On	Fire
18	5.5	500	11	5	4	On	Fire

TABLE 7 (cont'd.)

RUN NO.	ABSOLUTE PRESS (PSIA)	FUEL PRESS (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITION ACTUATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITOR ACTUATOR	RAMARKS
19	5.5	500	15	5	10	On	No Fire
20	5.5	500	12	5	12	On	No Fire
21	5.5	500	22	5	13	On	No Fire
22	5.5	500	17	5	16	On	
23	3	500	10	5	6	On	Fire
24	3	500	13	5	13	On	Fire
25	3	500	11	5	14	On	No Fire
26	3	500	12	5	18	On	Fire
27	3	500	27	5	23	On	Fire
28	3	500	24	5	24	On	No Fire
29	3	500	24	5	25	On	No Fire
30	3	500	28	5	28	On	No Fire
31	3	500	32	5	31	On	Fire
32	3	500	32	5	37	On	Fire

TABLE 8

IMPINGEMENT TYPE NOZZLE - 8 NOZZLES IN SIMULATED FUEL CELL - DIAGONAL NOZZLE ARRANGEMENT - CHAMBER SPARK, CONTINUOUS ARC, 10,000 VOLT, 23 MILLI-AMP TRANSFORMER - JP-4 FUEL

RUN NO.	ABSOLUTE PRESS (PSIA)	FUEL PRESS (PSIG)	FUEL TEMP. (°F)	FLOW DURATION PRIOR TO IGNITION ACTUATION	FOG TEMP. (°F)	FOG CONDITION AT IGNITOR ACTUATION	REMARKS
1	AMB	500	48	5	45	On	Fire
2	AMB	500	50	5	48	On	Fire
3	AMB	500	50	5	48	On	Fire
4	AMB	500	58	5	56	On	Fire
5	AMB	500	59	5	60	On	No Fire
6	AMB	500	58	5	61	On	No Fire
7	AMB	500	70	5	65	On	No Fire
8	AMB	500	58	6	68	On	No Fire
9	10	500	55	5	44	On	Fire
10	10	500	65	5	45	On	Fire
11	10	500	63	5	48	On	No Fire
12	5.5	500	26	5	9	On	Fire
13	5.5	500	32	5	18	On	Fire
14	5.5	500	34	5	20	On	No Fire
15	5.5	500	32	5	23	On	No Fire
16	5.5	500	39	5	30	On	No Fire
17	5.5	500	51	5	36	On	No Fire
18	5.5	500	62	5	43	On	No Fire

TABLE 8 (cont'd)

RUN NO.	ABSOLUTE PRESS (PSIA)	FUEL PRESS (PSIG)	FUEL TEMP. (°F)	FLOW DURATION PRIOR TO IGNIT-ION ACTUATION	FOG TEMP. (°F)	FOG CONDITION AT IGNITOR ACTUATION	RAMARKS
19	7.0	500	33	5	32	On	Fire
20	7.0	500	31	5	35	On	Fire
21	7.0	500	34	5	41	On	No Fire
22	7.0	500	47	5	47	On	No Fire

TABLE 9

IMPINGEMENT TYPE NOZZLE - 8 NOZZLES IN SIMULATED FUEL CELL -
DIAGONAL NOZZLE ARRANGEMENT - TWO GRAM MAGNESIUM SILASTIC PELLET IGNITION SOURCE - JP-4 FUEL

RUN NO.	ABSOLUTE PRESSURE (PSIA)	FUEL PRESS (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITOR ACTUATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITOR ACTUATION	REMARKS
1	14.7	500	98	5	65	On	Fire
2	14.7	500	114	5	75	On	Fire
3	14.7	500	115	5	84	On	Fire
4	14.7	500	94	5	90	On	Fire
5	14.7	500	128	5	92	On	Fire
6	14.7	500	132	[illegible]	100	On	No Fire
7	10.0	500	59	5	46	On	Fire
8	10.0	500	59	5	55	On	No Fire
9	10.0	500	71	5	65	On	No Fire
10	10.0	500	89	5	76	On	No Fire
11	10.0	500	96	5	80	On	No Fire
12	10.0	500	115	5	92	On	No Fire

TABLE 9 (Cont'd.)

RUN NO.	ABSOLUTE PRESSURE (PSIA)	FUEL PRESS (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITOR ACTUATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITOR ACTUATION	REMARKS
13	7.0	500	20	5	20	On	Fire
14	7.0	500	44	5	34	On	Fire
15	7.0	500	61	5	50	On	No Fire
16	5.5	500	32	5	29	On	No Fire
17	5.5	500	41	5	44	On	No Fire

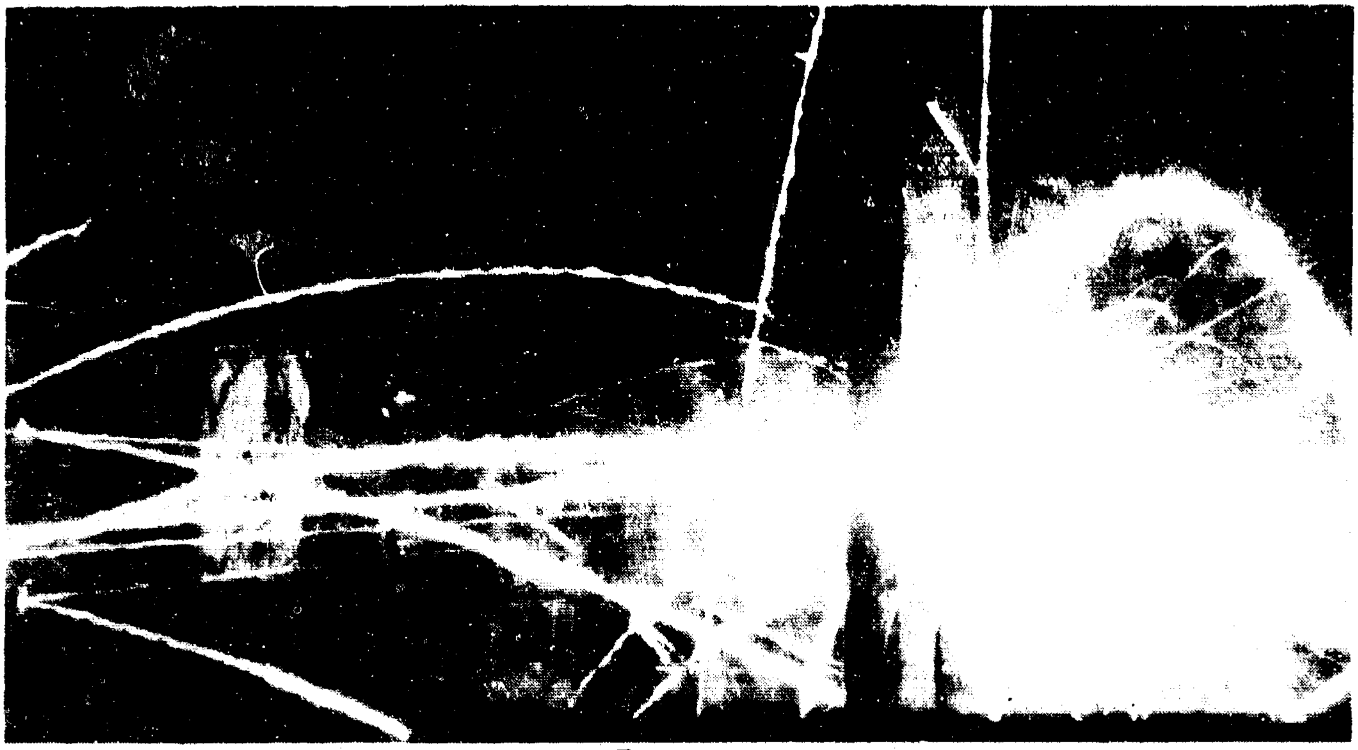


Figure 20
Functioning Incendiary Pellet

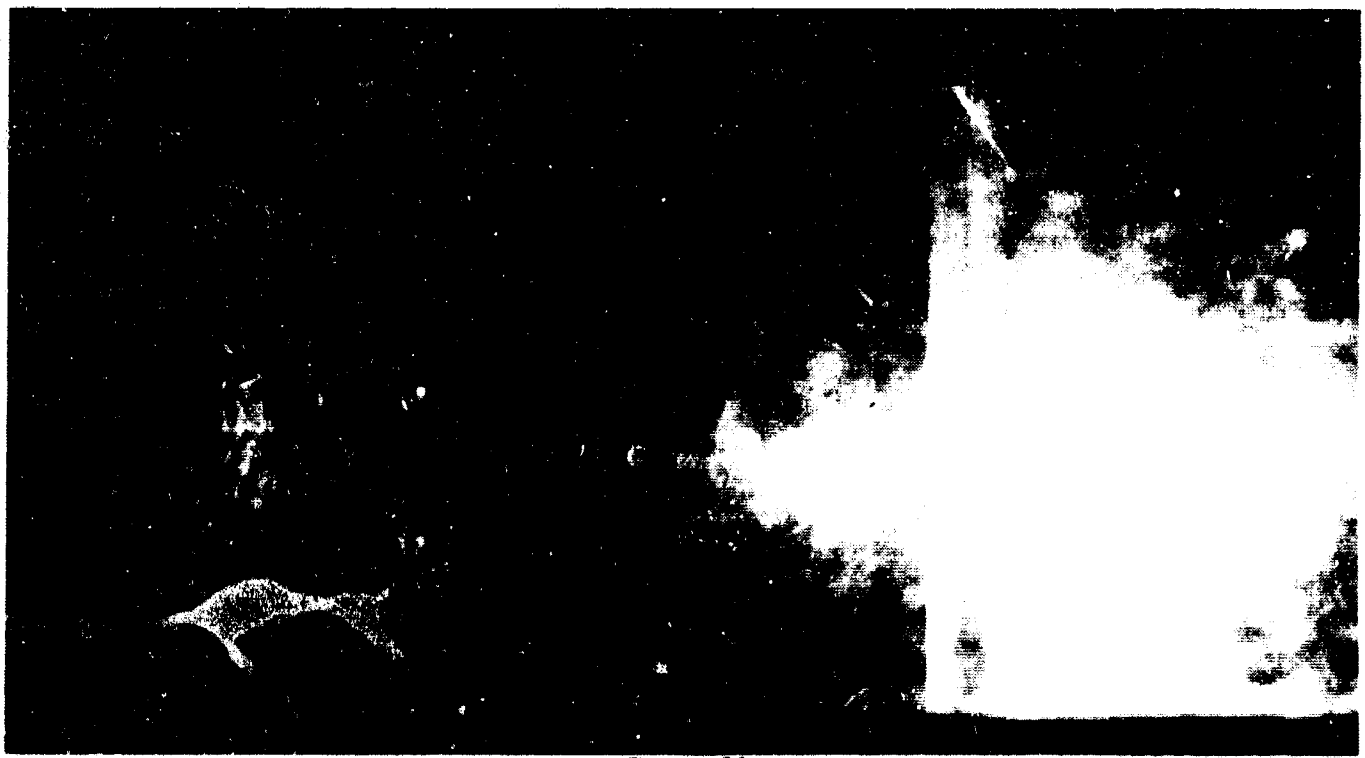


Figure 21
Functioning 50 Caliber API

During ignition studies of the vapor and fog with the incendiary ignition source an initial test was run to determine if the incendiary released sufficient energy to open the lids of the box, thus negating fog inerting effects due to the large amounts of fresh air available to the fogged chamber. The lids did not open and no pressure rise occurred within the chamber when the incendiary was functioned. This indicated that the initial ignition for all tests was occurring within the fuel chamber itself.

Although the incendiary tests were designed to simulate .50 caliber gunfire conditions, the tests were considered more severe for several reasons. These include total energy release, burn time and static location of source. In this instance, the total equivalent .50 caliber incendiary energy is released in the fuel cell while in actual gunfire tests, the incendiary energy release may be significantly less where the quantity of functioning incendiary is dependent upon the amount of bullet jacket that is torn away from the bullet in passing through the fuel cell and aircraft structure. The actual .50 caliber incendiary burn time when functioning occurs is approximately 50 milliseconds whereas the incendiary pellets used in this test had an effective burn time of 1.5 seconds. This, coupled with the fact that the pellets were held in place thus releasing all the heat energy in a single location within the chamber make this test considerably more severe than a gunfire test where the heat energy is dispersed more evenly through the fog heat sink volume due to projectile travel.

3. Milestone Status

The milestone status Figure 25 shows the limit of completion. The design and fabrication of gunfire specimens, gunfire test support and F-4 fuel fog system design trade off were not completed due to the termination of the program.

Figure 22
Rich Limit for JP-4 Under Dynamic Fog Condition Using Bete Impingement Type Nozzles (PT-5) - 14 Joule Capacitance Spark Ignition Source

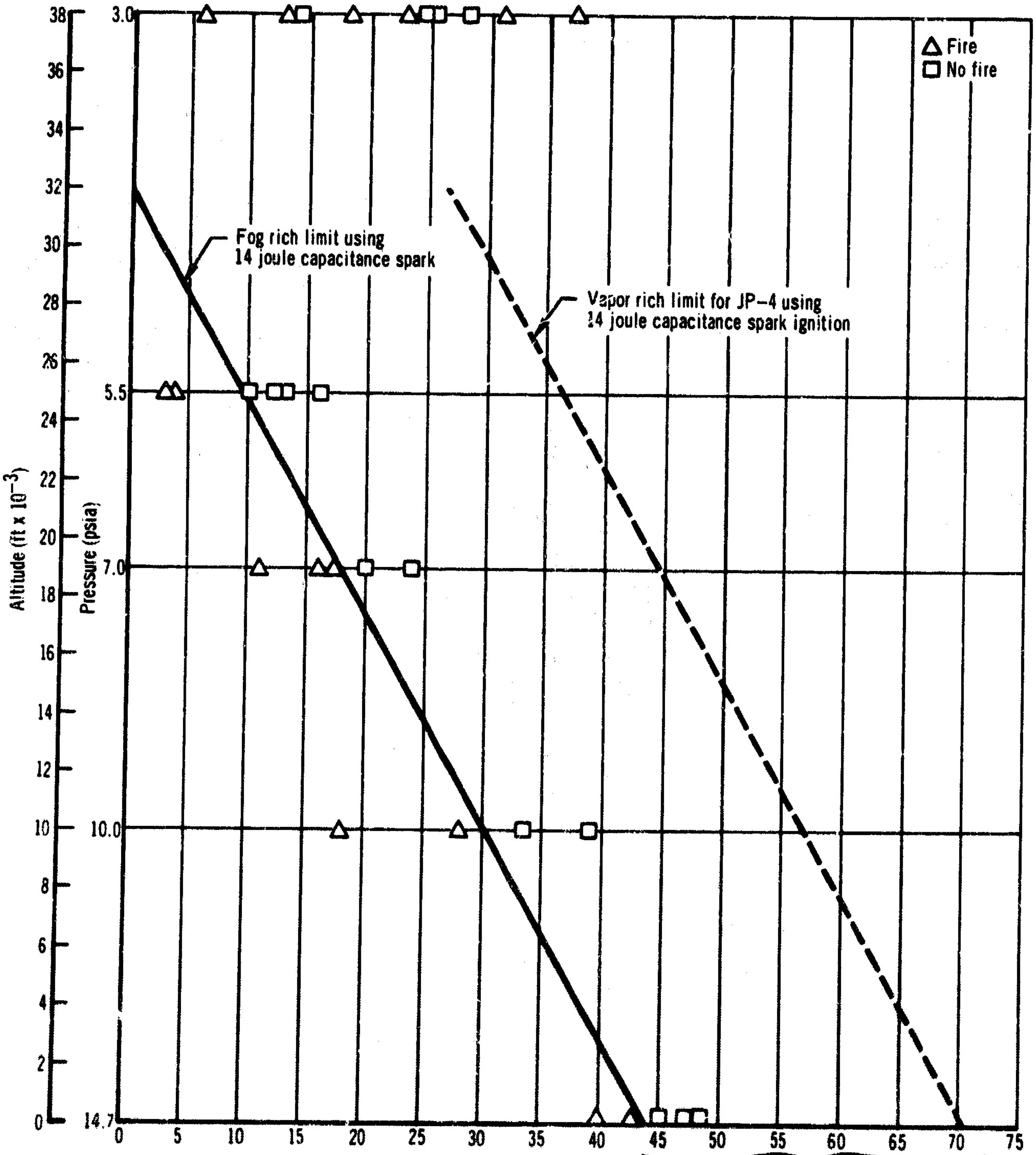


Figure 23
Rich Limit for JP–4 Under Dynamic Fog Condition Using
Bete Impingement Type Nozzles (PT–5) – 23 Joule
Transformer Spark Ignition Source

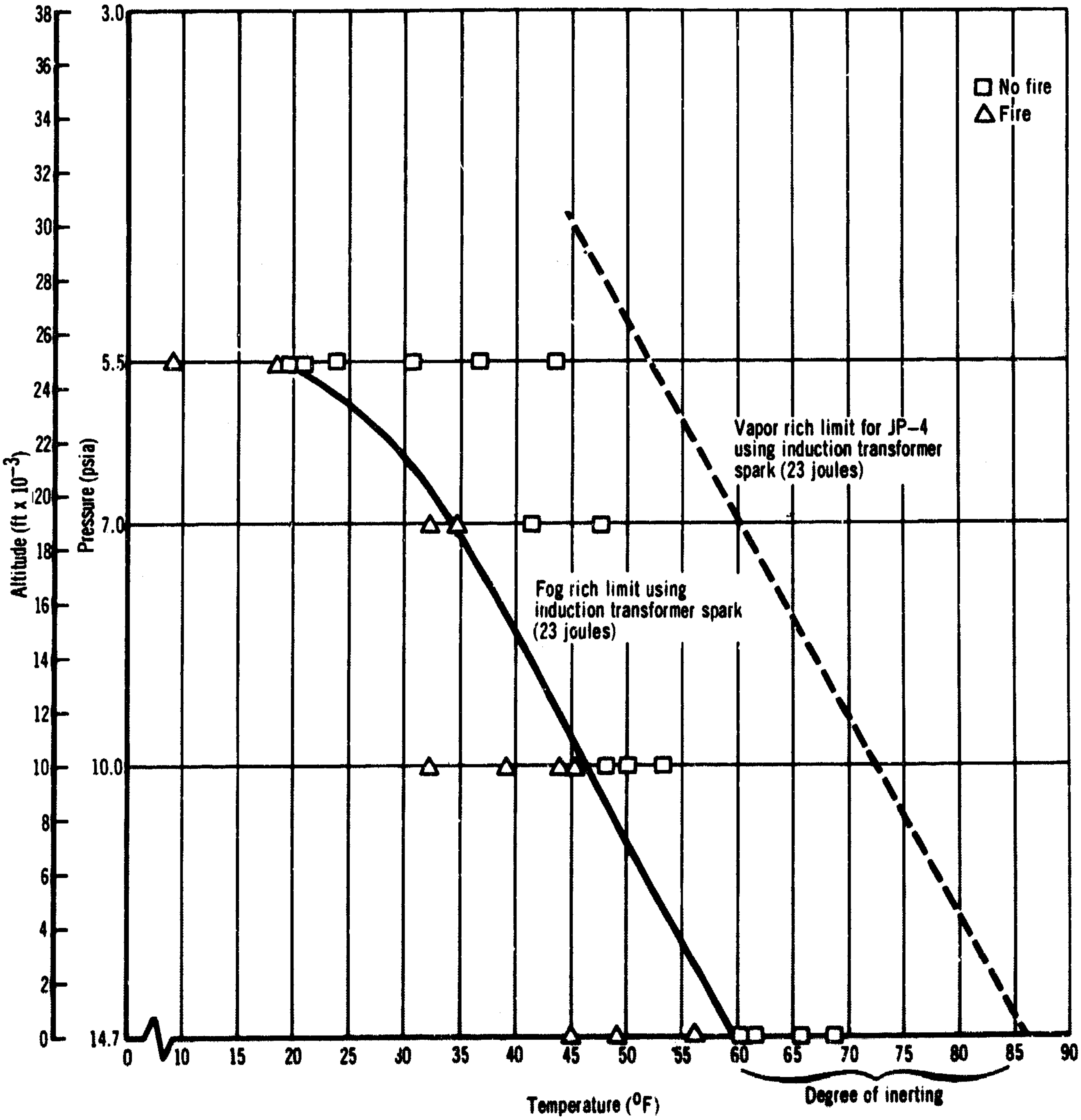
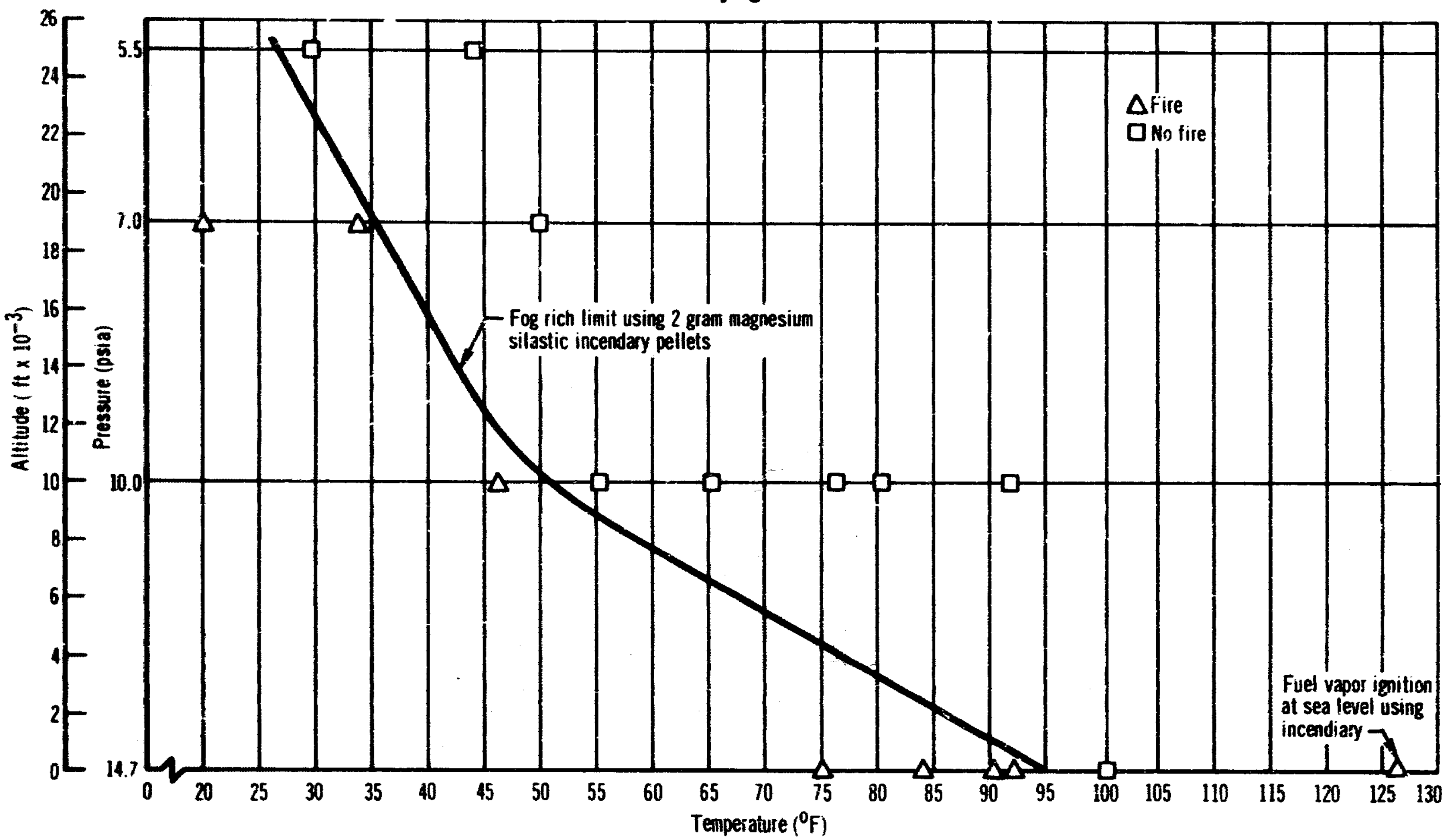


Figure 24
Rich Limit for JP-4 Under Dynamic Fog Condition
Using Bete Impingement Type Nozzles (PT-5I)
– Incendiary Ignition Source



FUEL FOG – FUEL CELL INERTING
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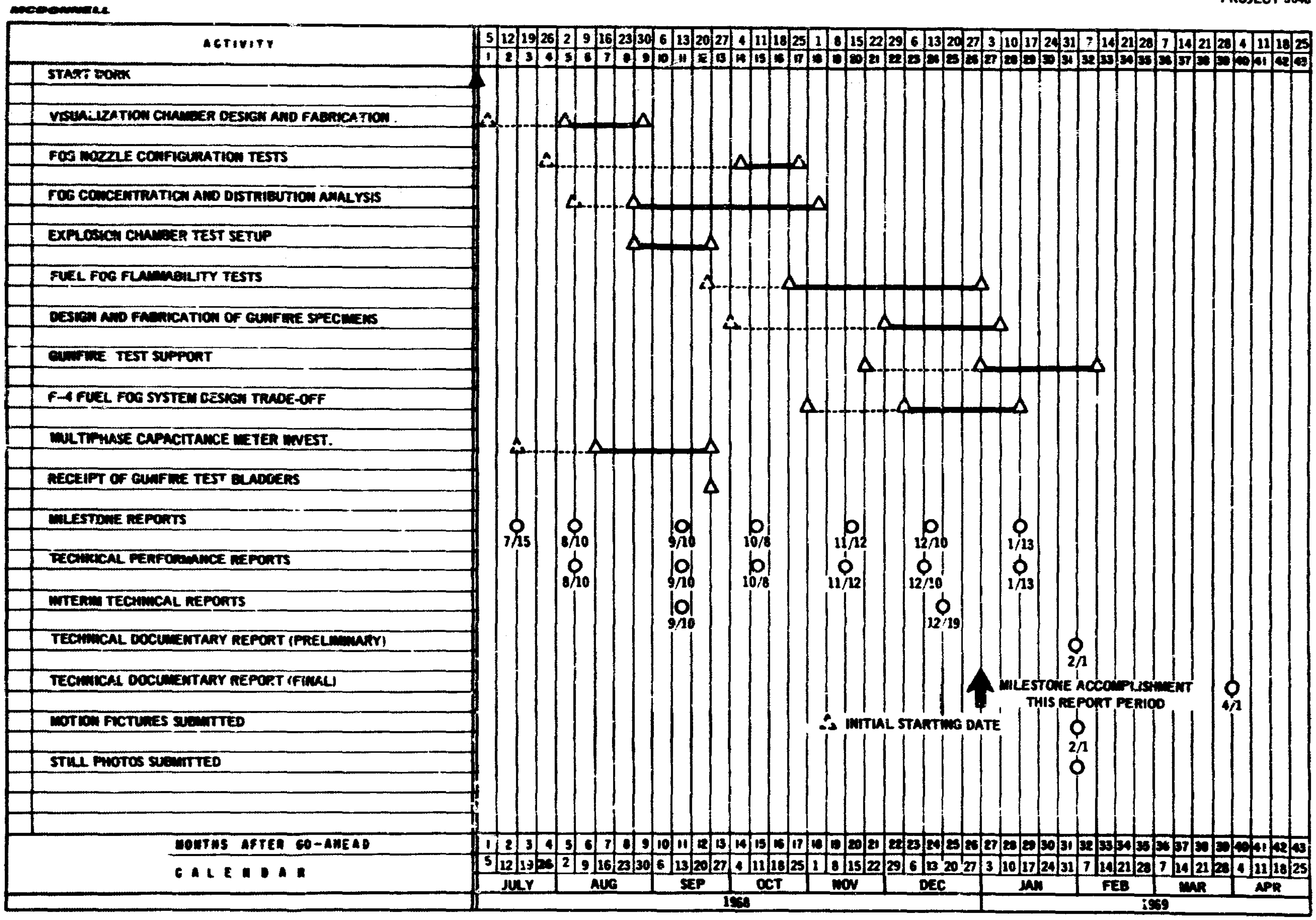
Figure 25
R&D Milestone Forecast



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SECTION IV

MDC IGNITION STUDIES

1. Nozzle Evaluation Tests

The company funded ignition study program was undertaken to confirm the fuel fog overrich theory in that a literature review revealed that earlier similar attempts by the British Ministry of Technology and the Douglas Aircraft Co. (Reference 1) were partially or totally unsuccessful. Further, cursory in-house testing confirmed these results. It was, therefore deemed advisable to investigate the controlling parameters before proceeding into the main body of the Air Force funded program.

An instrumented test chamber was built, as shown in Figure 26. The chamber was made up of a standard eight inch diameter schedule 40 stainless steel "Y" section. A one inch thick plexiglass window for viewing the fog, spark and ignition was bolted to the flange side arm.

The fog nozzle, air purge lines, and ignition probe were passed through the upper flange closure. The ignitor spark gap was located five inches below the nozzle outlet. Ignitors of approximately 0.1 joule and 14 joule energy were used as standard ignition sources. The 0.1 joule ignitor was a continuous type sparking device deriving it's energy from an automobile spark coil while the 14 joule sparker was a capacitance spark ignitor.

A relief valve was employed in the lower flange closure, for air purging and pressure relief of the chamber.

A liquid nitrogen cooling coil wrapped around the test chamber, not shown in Figure 26 was used to control the chamber wall and subsequently the fog temperature. Earlier tests revealed that the fog temperature quickly assumes and stabilizes to within a few degrees of the chamber wall temperature even under dynamic flow conditions.

Instrumentation of the ignition test chamber included: fuel pressure and temperature, fog and chamber wall temperature and chamber pressure. The chamber pressure transducer output was photographically recorded utilizing an oscilloscope. Figures 27 and 28 are typical oscilloscope traces of lean, rich and no fire pressure profiles. Each vertical division equals 30.8 psi thus the lean fire exhibited 110 psig or the theoretical maximum for atmospheric hydrocarbon explosions.

All nozzles, both pneumatic and hydraulic types, that were ignition tested were studied in this chamber. These include pneumatic nozzles of the paint spray, sonic and nebulizer type, and hydraulic nozzles of the simplex and impingement type. Over 400 test runs with JP-4 and JP-5 were made under varying controlled conditions. Representative results are shown in Tables 2 through 6.

From this series of tests it was shown that the process of spraying fuel in finely divided particles into an ullage space does in fact have an inerting effect. Calculations of the effective fog concentration indicate that only 0.14 lb fuel per

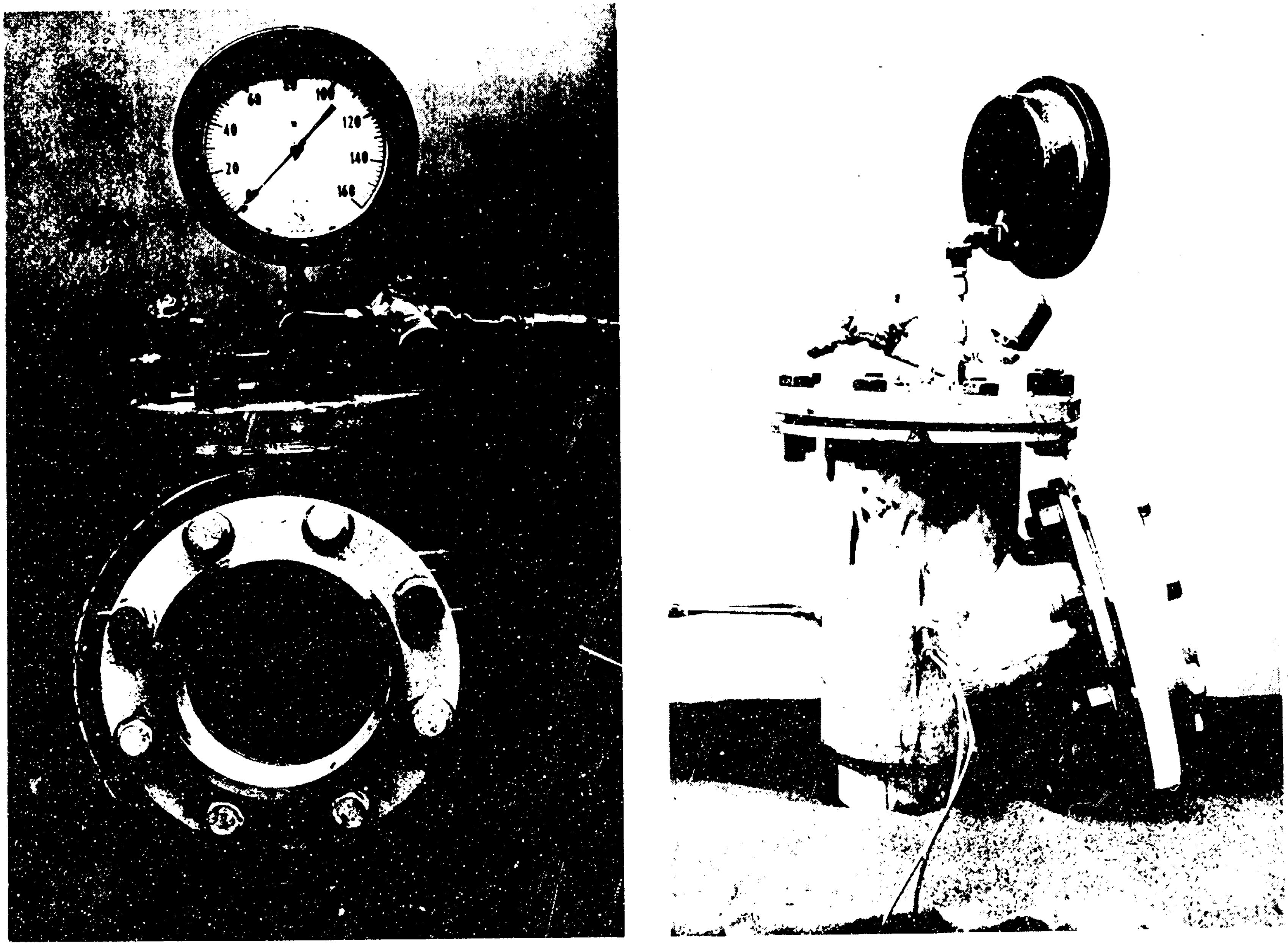

Figure 26
Ignition Chamber

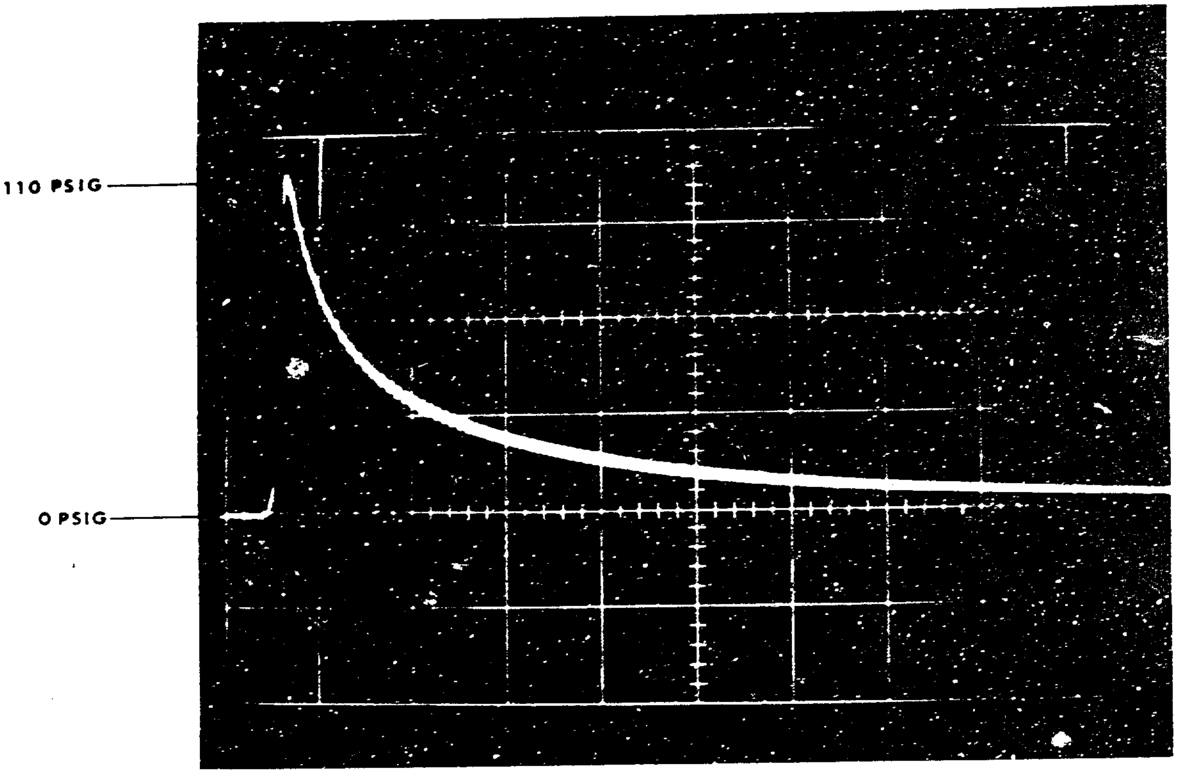

Figure 27 Scope Trace – Lean Fire Condition

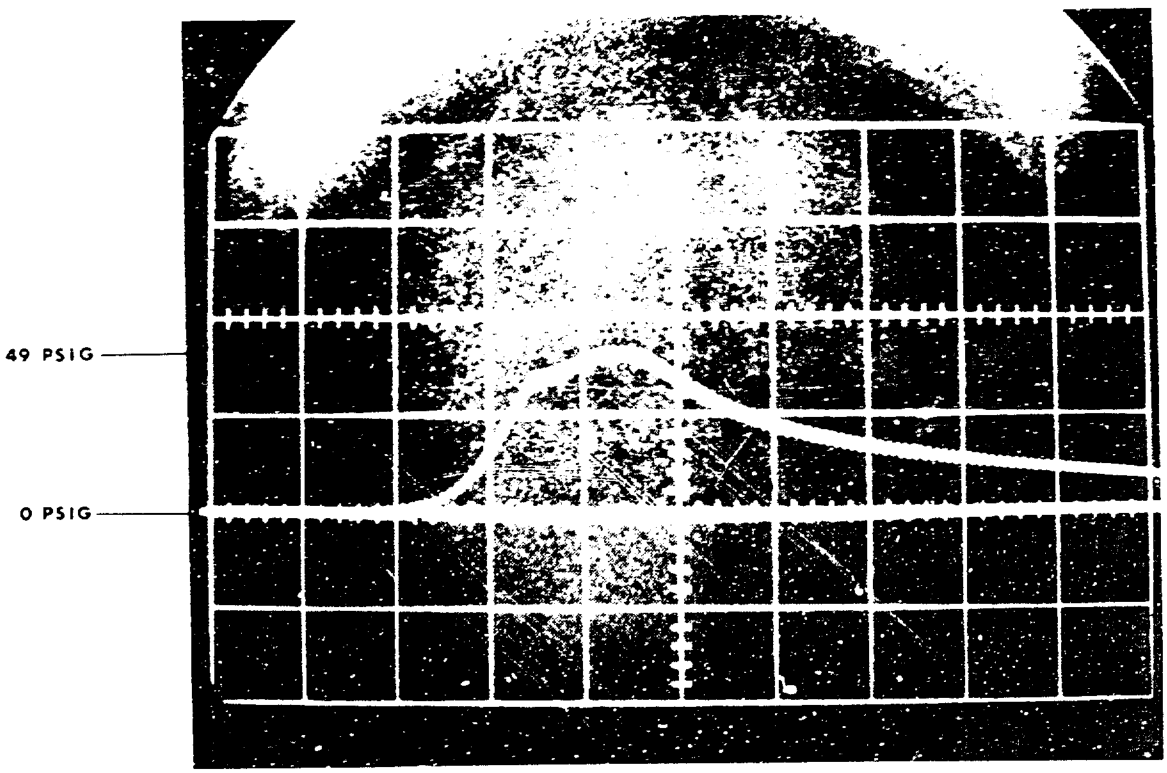

Figure 28 Scope Trace

a. Upper Trace – Rich Fire b. Lower Trace – No Fire

pound of air was being produced by the most efficient inerting impingement type nozzle. The problem of making the fuel fog inerting system a reality thereby seems to resolve itself to finding or developing a fog generating system capable of producing the required 0.28 pound fuel per pound air hydraulically.

Under all conditions the hydraulic nozzle proved to be superior to the pneumatic nozzle in fog inerting ability although total inerting over the entire fuel flammability range was not attained. Inerting capabilities of the hydraulic nozzles amounted to 35°F rich limit surpression for JP-4 whereas the most efficient pneumatic sonic nozzle using fuel saturated air as the pneumatic supply was only able to surpress the rich limit 19°F. Subsequent tests run on the Air Force funded program showed a slightly lesser value of inerting for this same hydraulic impingement nozzle but this was due to impingement pin wearing and degradation due to fires thus less efficiency in producing fog.

Tests were conducted using hydraulic nozzles to determine the relationship if any, between fuel temperature and fog temperature in inerting effectiveness. Fuel temperatures as high as 110°F, while the fog temperature was regulated to 35°F were run and the results are shown in Table 10. It can readily be seen from this data that a differential temperature to 75°F has no effect on the inerting capability of the system. Improvement of the sonic pneumatic nozzle was attempted in this same manner where the pneumatic air supply was heated to 210°F in order to determine if a more efficient breakup of the fuel particles could be attained due to the decrease in viscosity of the fluid brought on by increasing its temperature with the hot air. It can be seen from Table 3 that no increased inerting effect was obtained.

An attempt was made to improve the inerting capability of the system by using deoxygenated fuel with the hydraulic impingement nozzle. A vacuum to 3 pisa was drawn on a container of fuel and held for one hour, then the fuel was pumped through the nozzle and ignition tested. Once again no improvement over previous data was obtained as can be seen in Table 11. This same test was repeated, only the fuel container was back filled to 14.7 psia with nitrogen before pumping through the nozzle. Ignition temperature at ambient pressures remained the same as reported for this nozzle.

A marked improvement was seen in the system ability to inert when the fuel supply was pressurized to 500 psig with nitrogen then fed into the nozzles. The inerting improvement established in these tests was time dependent; time being that period that the fuel is fogged into the chamber. This can be noted in Table 12.

2. Fuel Variations

On the basis of the theory that the previously measured static electric charge of 500 volts on the fog particles cause coalescence and thereby a reduction in fog concentration, Shell's ASA-3 antistatic additive was obtained from WPAFB for testing. Ignition studies were run to determine if this additive would improve the fuel fog inerting capability. The results of these tests showed no improvement over the previous inerting capabilities. The tests were conducted with the following concentrations and variations.

TABLE 10

HYDRAULIC IMPINGEMENT NOZZLE BETE PT-5 - RIGID CHAMBER - ΔT TESTS JP-4 FUEL

RUN NO.	FUEL PRESS (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITOR ACTUATION (MIN)	FOG TEMP (°F)	CELL TEMP (°F)	FOG CONDITION AT IGNITOR ACTIVATION	REMARKS
1	500	38	3	33	26	On	Fire
2	500	67	3	35	27	On	Fire
3	500	110	2	35	12	On	Fire
4	500	43	1.5	36	34	On	Fire
5	500	42	3	39	36	On	Fire
6	500	54	1.5	39	38	On	Fire
7	500	68	3	40	35	On	No Fire
8	500	109	1	40	23	On	No Fire

TABLE 11

HYDRAULIC IMPINGEMENT NOZZLE BETE PT-5 - RIGID CHAMBER - DEOXYGENATED JP-4 FUEL BY EVACUATION TO 3 PSIA

RUN NO.	FUEL PRESS (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITOR ACTUATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITOR ACTIVATION	REMARKS
1	500	50	1	42	On	Fire
2	500	50	1	42	On	Fire
3	500	50	1	42	On	Fire
4	500	50	1	42	On	No Fire
5	500	50	1	44	On	No Fire
6	500	50	1	45	On	No Fire
7	500	50	1	49	On	No Fire
8	500	50	1	49	On	No Fire
DEOXYGENATED JP-4 FUEL BY EVACUATION TO 3 PSIA AND BACKFILLED TO 14.7 PSIA WITH NITROGEN						
9	500	50	1	31	On	Fire
10	500	50	3	35	On	Fire
11	500	50	3	39	On	Fire
12	500	50	3	41	On	No Fire
13	500	50	3	43	On	No Fire
14	500	50	3	43	On	Fire
15	500	50	3	45	On	No Fire

TABLE 12

HYDRAULIC IMPINGEMENT NOZZLE BETE PT-5 RIGID CHAMBER - NITROGEN PRESSURIZED SUPPLY TANK - JP-4 FUEL

RUN NO.	FUEL PRESS (PSIG)	FUEL TEMP (°F)	FLOW DURATION PRIOR TO IGNITION ACTIVATION (MIN)	FOG TEMP (°F)	FOG CONDITION AT IGNITOR ACTUATION	REMARKS
1	500	45	6	26	On	No Fire
2	500	45	4	29	On	No Fire
3	500	45	3	29	On	Fire
4	500	45	3	32	On	Fire
5	500	45	1	33	On	No Fire
6	500	45	3	34	On	No Fire
7	500	45	1	35	On	Fire
8	500	45	1	38	On	No Fire

(a) 0.75 mg ASA-3/liter JP-4

(b) 1.0 mg ASA-3/liter JP-4

(c) 7.5 mg ASA-3/liter JP-4

(d) 1.0 mg ASA-3/liter JP-4 + 1.25 cc Heptance

(e) 1.0 mg ASA-3 dissolved in 10 cc tolune/liter JP-4

(f) 10.0 cc Heptance/4000 cc JP-4

Table 13 includes data from these tests.

Some question was raised as to whether fogging or stripping of the more volatile components of JP-4 was responsible for the 35°F depression in the rich flammability limit. To answer this question, a pure compound, N-heptane, was substituted for the JP-4, and ignition studies were made. If stripping was responsible, then no rich flammability temperature limit depression would be apparent. The test sequence, using N-heptane, did demonstrate a 40°F depression in the rich flammability limit, thereby verifying that the fog was responsible for the inerting. Results of this test are presented in Table 14.

TABLE 13

IMPINGEMENT TYPE NOZZLE - ANTI-STATIC ADDITIVE

RUN NO.	FUEL PRESS (PSIG)	FUEL TEMP. (°F)	FLOW DURATION PRIOR TO IGNITOR ACTUATION (MIN)	FOG TEMP (°F)	CHAMBER TEMP.	FOG CONDITION AT IGNITOR ACTUATOR	REMARKS
0.001 GRAM ANTI-STATIC ADDITIVE PER LITER JP-4 FUEL							
1	500	42	1	25	36	On	Fire
2	500	42	1	29	36	On	Fire
3	500	44	1	34	38	On	Fire
4	500	44	1	40	40	On	No Fire
0.1 GRAM ANTI-STATIC ADDITIVE PER LITER JP-4 FUEL							
1	500	38	1	23	46	On	Fire
2	500	38	1	28	38	On	Fire
3	500	38	1	30	38	On	Fire
4	500	41	1	34	38	On	Fire
5	500	41	1	36	42	On	Fire
6	475	44	1	40	38	On	No Fire
0.00075 GRAM ANTI-STATIC ADDITIVE DISSOLVED IN 10 CUBIC CENTIMETERS TOLUENE PER LITER JP-4							
1	500	68	1	30	36	On	Fire
2	500	46	1	33	38	On	Fire
3	500	38	4	34	38	On	Fire
4	500	68	1	40	41	On	No Fire

TABLE 14

IMPINGEMENT TYPE NOZZLE - HEPTANE FUEL - PRESSURE FED SYSTEM

RUN NO.	FUEL PRESS (PSIG)	FUEL TEMP. (°F)	FLOW DURATION PRIOR TO IGNITOR ACTUATION (MIN)	FOG TEMP. (°F)	CHAMBER TEMP. (°F)	FOG CONDITION AT IGNITOR ACTIVATION	REMARKS
1	500	60	1	60	60	On	No Fire
2	500	60	1	58	58	On	No Fire
3	500	60	1	56	56	On	No Fire
4	500	60	1	41	34	On	No Fire
5	500	60	1	39	38	On	No Fire
6	500	60	1	36	32	On	No Fire
7	500	60	1	34	28	On	No Fire
8	500	60	1	33	28	On	No Fire
9	500	60	1	29	21	On	Fire
VAPOR PRESSURE STUDIES SHOWED THE RICH LIMIT AT AMBIENT ALTITUDE EQUAL TO 70°F							

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

Tests have shown that fuel when sprayed into the ullage space of a fuel cell in the form of fog (10 to 100 micron particles) acts as a vapor adding to the natural vapor concentration, thereby, reducing the flammability zone temperature limits. Inerting by this method proved to be only partially effective in that an apparent limiting concentration of fuel fog was reached, that being well below the fuel to air concentration needed for inerting over the full temperature range encountered by aircraft. Fog concentrations on the order of 0.14 lb. fuel/lb. air were produced as indicated in ignition tests whereas 0.28 lb. fuel/lb. air is needed for inerting over the full operating range of temperature. Verification of the maximum obtainable concentration of 0.14 lb. fuel/lb. air could only be made through ignition studies as attempts to sample the fog by various methods including syringe, settling device and vacuum bottle failed due to data scatter.

Hydraulic type nozzles proved far superior to the pneumatic nozzles although both showed an ability to partially inert the system. Hydraulic nozzles were able to surpress the rich flammable temperature limit of JP-4 from 70°F to 35°F whereas pneumatic nozzles were only able to surpress this limit to 55°F. With hydraulic nozzles this degree of surpression remained relatively constant for changes in nozzle per unit ullage volume and decreases in ullage pressure for specific ignition sources. This data suggests that a maximum fog or particle concentration had been reached with the nozzles tested.

Of the hydraulic nozzles tested the impingement type proved to be the more effective as an inerting device. The reason for this is the more efficient and complete breakup of the fluid stream caused by subjecting the fluid stream to the impingement pin.

Ignition energies proved to be very important in the establishment of flammability data. Rich limits for JP-4, both under vapor equilibrium and dynamic fog conditions varied as the ignition energy changed. This occurred to a point where the ignition source energy became sufficient to show the true flammable limit of the fuel. This energy was obtained by both electrical and incendiary sources of 23 joules and approximately 12,000 joules respectively.

2. Recommendations

Although testing results obtained in this program indicate that inerting capability for the fog system is inadequate at low ambient temperatures inerting over the entire flammability temperature range appears possible if nozzles producing a fog of greater density can be developed. It is recommended that any further development on this system be directed to:

- Investigation of the properties governing the maximum obtainable fog concentration.

- Developing more efficient fog nozzles and measuring their inerting ability on an individual basis.

- Testing with high energy ignition sources including actual gun fire testing.

SECTION VI

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	Air Force Aero Propulsion Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio 45433

13. ABSTRACT

Inerting of aircraft fuel tanks to eliminate fires and explosions can be accomplished by a number of methods. Oxygen dilution with inert gases, flame arresting with open cell foam and chemical quenching using halogenated hydrocarbons are some of the more successful methods. Another approach, the subject of this report, is to maintain the ullage fuel rich by employing some of the liquid fuel itself in the form of a fog. The fuel fog system works on the principle that finely divided liquid fuel (fog) acts as if it were in the vapor state, adding to the natural fuel vapor concentration. The system consists of a distribution manifold with fog nozzles located to produce a uniform fog throughout the fuel cells under all degrees of ullage and dynamic flight conditions. Since the fuel itself is the inerting material; weight, volume and logistic penalties are low. The first phase of the program was to define the fuel fog concentration and distribution with respect to various nozzle configurations, grouping and flow rates. Qualitatively, it was concluded that a uniform fog distribution is no problem due to the high turbulence observed in the visualization chamber. Quantitative concentration data were inconclusive due to sampling difficulties which lead to data scatter. The Phase II ignition studies have defined the dynamic flammability zones for JP-4 using the most effective fog inerting nozzle with three ignition sources; 14 joule capacitance spark, 23 joule induction spark, and incendiary, equivalent in weight and energy to a .50 caliber A.P.I. Pre-termination of Phases III and IV, the gunfire tests and the comparison of the subject system with other candidate systems was mutually agreed upon due to the limited inerting capabilities shown by the fuel fog system.

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